

Impact of a carbon market on afforestation incentives: A real option approach

By

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the requirements of the degree of Master of Science.

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ABSTRACT

The study investigates farmers' decision to afforest marginal agricultural land to create carbon sinks in western Canada. A real option model, which incorporates price risks related to carbon and timber revenues as well as opportunity cost uncertainty, is used to assess the impact of a carbon market on farmers' afforestation decision. Irreversibility of the decision is also modeled by including sunk cost of forest establishment and the cost of reversing the afforestation process. In addition, the non-permanence impact on the profitability of afforestation was analyzed by assessing the effect of two non-permanence carbon accounting schemes.

Results indicate that both, actual non-permanence policies and the presence of real options, have a significant negative impact on afforestation incentives. However, the carbon market has a positive effect as it increases the expected revenues to afforestation and also represents a diversification opportunity. Yet, even in the presence of a carbon market the investment barrier remains considerable. Despite the positive effect of the carbon market, results show that unless carbon prices reach levels well above \$100/tC a subsidization of afforestation cost is needed in order to generate substantial GHG abatement from marginal agricultural land afforestation in western Canada.

RÉSUMÉ

La présente étude enquête sur la propension des agriculteurs à reboiser les terres agricoles marginales de l'ouest canadien dans le but de créer des puits de carbone. Un modèle d'option réelle, incorporant les risques reliés aux prix des produits forestier et du carbone ainsi que ceux reliés au coût d'opportunité, est utilisé pour estimer l'impact d'un marché du carbone sur les incitatifs au reboisement. L'irréversibilité du reboisement est également prise en ligne de compte par l'inclusion des coûts irrécouvrables reliés à la reforestation ainsi que le coût que représenterait un retour aux fonctions agraires du terrain. De plus, l'impact de la non-permanence des puits de carbone sur la rentabilité du projet de reboisement est analysé en estimant l'impact de deux différents systèmes de mise en marché des services de séquestration.

Les résultats indiquent que les deux facteurs, soit la non-permanence des puits de carbone et la présence d'options réelles, ont un impact largement négatif sur les incitatifs au reboisement. Par contre, un marché du carbone a des effets positifs puisqu'il augmente les revenus et contribue à leur diversification. Toutefois, même en présence d'un marché du carbone les contraintes au reboisement demeurent considérables. En dépit de l'effet positif d'un marché du carbone, les résultats démontrent qu'à moins que le prix du carbone ne dépasse largement les 100\$/tC, une subvention des coûts de reboisement est nécessaire pour générer une quantité substantielle de puits de carbone sur les terre agricole marginales de l'ouest canadien.

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TABLE OF CONTENTS

ABSTRACT	i
RÉSUMÉ	ii
ACKNOWLEDGMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vi
LIST OF FIGURES	vii
 CHAPTER 1: Introduction	
1.1 Background Information	1
1.2 Problem Statement	5
1.3 Research Objectives	6
1.4 Case Study	6
1.5 Outline of the Study	7
 CHAPTER 2: Literature Review	
2.1 Estimation of Carbon Sequestration Cost	9
2.2 Theories of Farmer's Adoption Behavior	17
2.3 Empirical Literature on Barriers to Adoption	21
2.4 Real Option Theory	24
2.5 Carbon Accounting: Addressing Non-Permanence	34
2.6 Agroforestry and Hybrid Poplar	38
 CHAPTER 3: Model	
3.1 Model 1	41
3.2 Model 2: Stochastic Opportunity Cost and Reversibility	49

CHAPTER 4: Data and Estimation

4.1 Discount Rate	59
4.2 Cost of Conversion to Forestry	59
4.3 Cost of Conversion to Agriculture	60
4.4 Agricultural Revenues	61
4.5 Forestry Revenues	71
4.6 Carbon Yields	80

CHAPTER 5: Results and Discussion

5.1 Budgeting (NPV) Analysis	83
5.2 Results from Model 1 and 1a: Real Option Analysis	85
5.3 Results from Model 2 and 2a: Including Opportunity Cost Uncertainty and Reversibility	91
5.4 Sensitivity Analysis	95
5.5 Potential Policies for TC Scenario	99

CHAPTER 6: Summary and Conclusion

6.1 Summary	104
6.2 Synopsis of Major Findings	105
6.3 Policy Implications	107
6.4 Limitations and Further Research	109
6.5 Conclusion	110

REFERENCES	111
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APPENDIX 1	118
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APPENDIX 2	120
-------------------	-----

APPENDIX 3	121
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LIST OF TABLES

Table 2.1	Value of TCs given a value of \$15 and \$25 for permanent credits.....	37
Table 4.1	Hybrid poplar establishment cost.....	60
Table 4.2	Volatility estimates.....	65
Table 4.3	Selection order criteria for agricultural net real revenues.....	67
Table 4.4	Ljung-Box Q-statistic for the residual of the AR(1) model of the agricultural revenues.....	68
Table 4.5	DF-GLS results for agricultural net real revenues.....	70
Table 4.6	Selection order criteria for timber net real revenues.....	75
Table 4.7	Ljung-Box Q-statistic for the residual of the AR(4) model of the timber revenues.....	75
Table 4.8	DF-GLS results for timber net real revenues.....	77
Table 4.9	Ljung-Box Q-statistic for the residual of the AR(3) model of the timber revenues.....	77
Table 4.10	Carbon pools in tC/ha.....	80
Table 5.1	Sensitivity indexes for the temporary credits scenario.....	97

LIST OF FIGURES

Figure 2.1	Investment threshold under NPV and real option approaches.....	27
Figure 2.2	Entry and exit thresholds as functions of return's volatility (σ).....	30
Figure 2.3	Chapman-Richards growth curve for hybrid poplar in boreal regions	40
Figure 2.4	Hybrid Poplar cost distribution.....	40
Figure 4.1	Saskatchewan tame hay yield in tons per acre (1971-2002).....	62
Figure 4.2	Saskatchewan tame hay price in Canadian nominal dollars per ton (1971-2002).....	63
Figure 4.3	Saskatchewan tame hay nominal revenues in Canadian dollars per ton (1971-2002).....	63
Figure 4.4	Saskatchewan tame hay net real revenues per hectare in Canadian dollars per tons (1971-2002).....	64
Figure 4.5	Partial autocorrelation function of annual agricultural net real revenues ($R_{a,t}$).....	67
Figure 4.6	Autocorrelation function of the residuals from regression $R_{a,t}=\alpha_0+\alpha_1R_{a,t-1}$	68
Figure 4.7	Partial autocorrelation function of the residuals from regression $R_{a,t}=\alpha_0+\alpha_1R_{a,t-1}$	69
Figure 4.8	Gross nominal timber sale revenues per cubic meter.....	72
Figure 4.9	Gross real timber sale revenues per cubic meter.....	72
Figure 4.10	Net real timber sale revenues per cubic meter.....	74
Figure 4.11	Partial autocorrelation function of forestry net real revenues ($R_{f,t}$)....	75
Figure 4.12	Autocorrelation function of the residuals from regression $R_{a,t}=\alpha_0+\alpha_1R_{f,t-1}+\alpha_2R_{f,t-2}+\alpha_3R_{f,t-3}+\alpha_4R_{f,t-4}$	76

Figure 4.13	Partial autocorrelation function of the residuals from regression	
	$R_{a,t} = \alpha_0 + \alpha_1 R_{f,t-1} + \alpha_2 R_{f,t-2} + \alpha_3 R_{f,t-3} + \alpha_4 R_{f,t-4}$	76
Figure 4.14	SO ₂ Allowance price index	78
Figure 4.15	Carbon yield curves in tons of C per hectare	82
Figure 5.1	NPV investment threshold and expected revenues from various carbon accounting scheme	84
Figure 5.2	Real option investment threshold given uncertain forestry revenues and irreversible afforestation	86
Figure 5.3	Real option value without carbon markets	87
Figure 5.4	Real option value in presence of carbon markets	89
Figure 5.5	Forestry revenues and investment threshold as a function of carbon price	90
Figure 5.6	Real option investment thresholds for temporary credits scenario	92
Figure 5.7	Cumulative afforestation investment probabilities over 10 years	94
Figure 5.8	Sensitivity of the real option optimal investment threshold as a function of forestry revenues volatility	101
Figure 5.9	Minimum carbon price to trigger afforestation on marginal agricultural land	103

Chapter 1: Introduction

1.1 Background Information

Due to increasing human population and activity, climate change has now become a central issue for the world community. Direct linkages between anthropogenic activity and global warming are now undeniable. If unabated, the scientific community estimates that increasing concentration of greenhouse gases (GHGs) will lead to a rise of 1.4°C to 5.8°C in global temperature and consequences are likely to include an increase in fresh water scarcity, biodiversity losses, and higher sea level which would harm coastal regions (UNFCCC, 2005). The need for speedy action is made clearer as the evidence of environmental damages keeps growing.

"Projected climate changes during the 21st century have the potential to lead to future large-scale and possibly irreversible changes in Earth systems resulting in impacts on continental and global scales."

IPCC, 2001b

The Kyoto Protocol (KP), which became legally binding as of February 16, 2005, is a first step in addressing global warming. To achieve a more responsible management of global GHG emissions, the KP requires from Annex 1¹ countries an average GHG emission reduction of 5% below 1990 levels. In addition, the United Kingdom (UK) advocated a 60% reduction of GHG emissions for all developed countries by 2050 to prevent major environmental damages (UK Government 2003). Negotiation on post-Kyoto efforts towards global warming mitigation and adaptation will start at the Montreal Conference of the Parties held in fall 2005.

¹ Annex 1 countries are the 36 industrialized countries and economies in transition listed in Annex 1 of the KP.

Under the current accord, Canada agreed to reduce its GHG emissions to 6% below its 1990 level. This commitment translates into a reduction of 270Mt of CO₂ eq² per year for the period of 2008-2012. In the longer term, the Canadian Minister of Environment, Stéphane Dion, expressed the federal government's intention to reduce the GHG emissions by 70% within the next 50 years (Globe and Mail, 2004). Both of these targets represent huge challenges for our economic system and using the lowest cost strategy becomes crucial to maintain the competitiveness of the Canadian economy on world markets.

To fulfill its Kyoto commitment the Canadian government released its "Project Green" during the spring of 2005. Since market-based tools are seen as the best way to achieve environmental goals in an economically efficient manner, they play a central role within the Canadian plan to address climate change. Within the projected carbon market, two domestic buyers can be identified; the large final emitters (LFEs) and the Climate Fund created and financed by the federal government. The LFEs, including the manufacturing, oil and gas, mining, and thermal electricity sectors, will be legally bound to provide at least 36 Mt of CO₂e per year in emissions reductions for the period 2008-2012. On the other hand, the Climate Fund is expected to purchase in the order of 75 to 115 Mt of CO₂e reductions on a yearly basis (Government of Canada, 2005).

² Mega tonne of CO₂ equivalent

Each of the buyers will have different sources from which to seek reductions. First, LFEs themselves are expected to create in-house reductions and surpluses from their efforts will be tradable. Also, two international mechanisms put in place by the United Nations Framework Convention on Climate Change (UNFCCC) will bring supplies to the market; the Clean Development Mechanism (CDM) will oversee projects within developing countries while Joint Implementation (JI) provides a framework for projects implemented in other Annex 1 countries. The last expected source of supply is the domestic market which will take the form of an Offset System (OS). The OS will include domestic projects from all sectors not covered under the LFE group. It is expected that most OS projects will be generated within the agricultural, forestry and landfill sectors.

Because of the open nature of the carbon market, the Canadian domestic market price is expected to be determined by international trade. The price of Kyoto compliance units in the European Union (EU) trading scheme, which is presently the largest market for GHG emissions allowances, was \$11/tonne of CO₂ eq to \$12.5/tonne of CO₂ eq for the year 2004 (\$40/tC to \$45.8/tC⁴) (Lecocq, 2004). However, the expected carbon price remains uncertain. The Canadian plan includes a price assurance at \$55/tC for LFEs, but the price could reach higher levels depending on future environmental and economic damages related to climate change, the speed of technological development, and political will to address the issue. Nevertheless, the price is not expected to be sustained at high levels as it would harm economic systems. In addition, the exclusion of the United States from the protocol reduces considerably the potential demand for Kyoto compliance units.

⁴ Exchange rate used was 0.64 CAN\$/€. Conversion ratio: 3.667 tonne of CO₂ eq =1tC.

Likewise, the future decision with regards to the inclusion of China and India in post Kyoto agreements add to the uncertainty of the future carbon price.

GHG abatement projects of various types will be proposed with their credits going to the market. One key distinction must be made. Projects can produce either emission reduction units (ERUs) or removal units (RMUs), the former being associated with fossil fuel emission reductions while the latter is the output of sequestration activities. This distinction is crucial as the value of ERUs and RMUs may differ for reasons to be presented later. Such a distinction is of great importance since sequestration projects are expected to be an important part of climate change mitigation efforts.

“The estimated global potential of biological mitigation options is on the order of 100 Gt C⁵ (cumulative) by year 2050, equivalent to about 10 to 20% of projected fossil-fuel emissions during that period, although there are substantial uncertainties associated with this estimate. Realization of this potential depends upon land and water availability as well as the rates of adoption of land management practices.”

IPCC, 2001a p.25

At the national level it is believed that carbon sinks from forestry and agriculture can play a major role towards the attainment of Canada's KP commitment since they have been identified as being low cost alternatives to other abatement strategies.

“One natural advantage Canada has in rising to the challenge of climate change is our vast forests and agricultural lands. Properly managed, these can be valuable in sequestering GHG emissions from the atmosphere.”

Government of Canada, 2005 p.iv

As was mentioned earlier, the two types of credits, RMUs and ERUs, differ in approach and will also differ in value. The fundamental difference between avoided fossil fuel emissions and carbon removals from sequestration is the issue of non-permanence. Both, fossil fuel reserves and biological carbon sinks, represent a potential supply of GHGs but what characterizes biological sinks is the uncertainty of their content since carbon enclosed within them could revert back to the atmosphere unexpectedly. Such reversals can be due to natural events, such as fire and pests, or anthropogenic behaviour (e.g. harvesting or a discontinuity in the application of best management practices (BMPs)). Hence, reductions in fossil fuel emissions are considered as permanent and low risk while removals through carbon sinks may be considered as temporary or riskier, thus yielding a discounted value for RMUs compared to ERUs.

Another key concern with regard to biosinks is the ability, or lack thereof, of public policies to effectively provide the incentives for private land owners to create biosinks. The design of the OS is therefore a central factor in determining the adoption level of the different land management practices. But while economic efficiency is vital, the OS must also provide environmental integrity and equity among stakeholders.

1.2 Problem Statement

This study has been designed to identify and investigate determinants of farmers' participation rates in creating biosinks as a GHG mitigation effort. Such knowledge becomes important in the elaboration of a least cost mitigation policy and the establishment of an OS for the attainment of Canada's Kyoto commitment. The study

⁵ Gt= gigatonnes or 1000 million tonnes

also evaluates potential policy designs that could affect this rate. Attention is given to risks associated with carbon markets and the adoption of BMPs leading to the establishment of biosinks. The issue of non-permanence is also addressed and its impact on BMPs adoption rates is investigated.

1.3 Research Objectives

- Develop a model to value risk and irreversibility in the adoption of best management practices.
- Use the model to value and assess the impact of adoption barriers created by uncertainty related to the adoption of BMPs and carbon price.
- Use the model to investigate potential solutions to the non-permanence issue.
- Use the model to investigate various institutional designs and policies that can alleviate barriers created by risk and irreversibility and discuss the implications of the results.

1.4 Case Study

As every carbon sequestration project will have its own peculiarities, a relevant case study on which to perform the economic analysis must be identified. The thesis will be based on the study of an afforestation project. This type of project was selected because of its recognized potential in mitigating GHG emissions. Also the existence of a sizable literature on the topic as well as the presence of risk and investment irreversibility inherent to afforestation projects makes it an ideal case study.

“...there can be considerable changes in market demand for the wood resulting in a certain level of risk.”

“The growing of hybrid poplar is a long term commitment with high initial costs and the possibility of no economic return for many years.”

AAFC, 2005

From a geographical point of view, Western Canada was selected in light of previous studies (McKenney et al. 2004, Van Kooten et al. 2000) which rank the Prairie region as being the most economically suitable for such a project. Also marginal agricultural land was chosen as it represents the lowest opportunity cost of land in the area that would meet the afforestation criterion under the KP⁶. In particular, land devoted to tame hay production has a small opportunity cost. In addition, time series of revenues and cost are available for such production. Finally, afforestation with hybrid poplar is selected based on results from Van Kooten et al. (2002) which present this species as best suited for landowners' preferences. The main argument being the short rotation of hybrid poplar which better suits farmers' preferences in terms of contract length.

1.5 Outline of the Thesis

Chapter two begins with a literature review of carbon sequestration cost estimation methodologies and the potential of afforestation for GHG mitigation. Theoretical and empirical literature on farmer's adoption behaviour is also surveyed to provide a better understanding of factors affecting the decision making process. Following this is a review of real option theory and empirical real option studies related to agriculture and forestry.

Then, carbon accounting methods used to address the issue of non-permanence are presented. The chapter ends with a review of agroforestry and the economic and technical aspects of hybrid poplar.

The third chapter develops two real option models used to investigate the afforestation incentives created by a carbon market and the presence of adoption barriers. The first model includes the volatility of forestry revenues and considers investment as irreversible. The second model adds to the previous one by including the volatility of agricultural revenues and the allowance for the costly reversion of the afforestation project.

The fourth chapter introduces data and estimation procedures used to estimate the baseline parameter values of the model. In addition, simulation techniques and carbon yield assumptions are detailed.

Chapter five presents the results obtained from real option models. As well, it includes a sensitivity analysis of the most important variables. Finally, the potential impact of various public policies on the behaviour of producers is investigated.

Chapter six presents the conclusion. It starts with a brief summary of the study followed by a synopsis of major findings, policy implications, limitations and suggestions for further research.

⁶ Under the Kyoto protocol, afforestation is defined as human induced establishment of forest on land that historically has not contained forest (usually within the last 50 years).

Chapter 2: Literature Review

2.1 Estimation of Carbon Sequestration Cost

The federal government has placed great importance to carbon sinks in their mitigation plans. A major reason for this is that the costs of sequestration are presumed to be modest. This section will serve as an inquiry into the economic potential of biosinks and most importantly it will identify the factors that affect sequestration costs and their estimation.

In order to create carbon sinks on agricultural land, farming techniques and land management have to be adapted and aligned with the environmental goal of carbon sequestration. In many cases agricultural producers will have to spend time and money to learn how to work with new techniques or new crops and they may have to invest in machinery or other forms of capital. New practices are usually second-best with respect to the farmer's profit and by changing their ways farmers have to forgo revenues from their conventional practices. Hence, farmers need to be provided with the appropriate incentives to overcome these costs and commit to any major land use change. Incentives needed to get farmers to create carbon sinks are the cost of sequestration.

Over the last ten years, many researchers have analyzed and estimated the costs of carbon sequestration in both agriculture (Schneider 2002, Schneider and McCarl 2002, Antle et al. 2002, Pautsch et al. 2001) and forestry/agroforestry (Van Kooten et al. 2000, Stavins 1999, Plantinga et al. 1999, and Parks and Hardie 1995). McCarl and Schneider (2000)

present a summary table of 13 studies that have estimated the costs of carbon sequestration from various tree planting strategies (p.143-144). The cost estimates reported range between \$0⁷ and \$400 per ton of carbon but most of them are between \$10 and \$50/tC. In the agricultural sector, Antle et al. (2002) provided estimates of \$10 to \$102/tC as the marginal cost of soil C sequestration in Iowa and Montana. Schneider and McCarl (2002) report an economic potential of 50 to 70 megatons for soil carbon sequestration on U.S. cropland at carbon prices below \$100/tC. Although results may vary significantly among studies, the general conclusion is that biosinks are cost effective and can play an important role in the reduction of GHG atmospheric concentration given an expected carbon price below \$100/tC.

However, some recent studies are less enthusiastic about the economic feasibility of carbon sinks. Manley et al. (2005) ran a meta-regression analysis on more than 100 source studies looking at the economics of no-till or reduced tillage adoption and the related carbon uptake. They conclude: "...the costs of creating carbon offsets by subsidizing a switch in tillage practices may be too high and, with some exceptions, not generally competitive with emissions reduction." p.58.

Looking at the forestry sector, Van Kooten et al. (2004) also used meta-analysis to look at 55 source studies and to investigate carbon sequestration potential. While acknowledging the possibility of forest sinks to be competitive they also mentioned that most previous studies did not account for the ephemeral nature of the sinks which should discount the

⁷ A sequestration cost of zero implies that the best management practice that creates the carbon benefits is just as profitable as conventional practices. Hence the producers should be indifferent between practices.

carbon benefits. In addition, a few sources of disparities among studies are outlined including the methodology used to estimate and report sequestration cost (average versus marginal costs) and the definition of carbon sink boundaries (inclusion of soil carbon accumulation and post harvest sinks). The inclusion of wood products as sinks is presented as being a key factor in determining the competitiveness of the forestry option. Finally, they point out that when opportunity cost of land is taken into account the cost of sequestration could be as high as \$1300/tC which contrasts with the results reported by McCarl and Schneider (2000).

Richards and Stokes (2004), in a comprehensive review of studies on forest carbon sequestration, report variation between studies with respect to cost estimation procedure, carbon yield, and carbon accounting method. Moreover, they stress the heterogeneity of methodologies used to model the cost of diverting land from its current use. As land is one of the main inputs in creating biosinks, its value is a prime determinant of sequestration costs.

Given the variance among these results, a better understanding of factors affecting cost estimates is desirable. Richards and Stokes' review (2004) differentiates between three methods used in the literature to model land conversion cost: bottom-up engineering, sectoral models, and econometric models. The first type, bottom-up engineering, is built with exogenous estimates of opportunity cost and input prices. Typically, this methodology does not allow for market responses and adjustments. Sectoral optimization models, by allowing for endogenous prices, account for macroeconomic aspects such as

the interrelationships between sectors or industries and therefore encompass supply and market responses. However, both approaches rely on pure profit maximization arguments and their main limitation is their inability to account for factors like the behavioral characteristics of individual decision making processes. On the other hand, econometric models enable researchers to analyze how landowners have historically allocated land use between agriculture and forestry and thus allow one to capture individual decision making characteristics and preferences.

In their review, Richards and Stokes (2004) compare results from these different modeling approaches when applied to the same geographical areas. They find that Richards' (1997) results for the delta states of the U.S., which came from the bottom-up engineering approach, are substantially lower than Stavins' (1999) estimates obtained using the econometric approach. For the states of Maine, South Carolina, and Wisconsin, similar conclusions are drawn when comparing Plantinga et al.'s (1999) results with those of Richards (1997). While some of the difference may be explained by the carbon yield assumed and the carbon accounting used in each study, some discrepancies remain and one may suppose that some unidentified individual decision making characteristics and preferences may play an important role in land use decisions.

Another interesting part of the literature looked at the potential of marginal agricultural land afforestation in western Canada. This category of study provides a great source of information as most studies relate to similar sequestration projects with a comparable geographical scope. These similarities allows for an easy comparison of the various

economic modeling approaches. Moreover they provide information about the potential of Canadian biosinks.

Van Kooten et al. (2000) completed an economic analysis of fast growing hybrid poplar on marginal agricultural land in Alberta (Alta) and British Columbia (BC). The cost engineering analysis included the opportunity cost of land and a planting cost of \$1270/ha. In this study, harvest did not occur until 50 years and it was assumed that upon harvest, revenues would offset carbon losses and future planting costs. This simple analysis, which did not considered non-permanence, lead to the promising results that even at a price of \$20/tonne of carbon (\$5.45/tonne of CO₂ eq.) and discounting physical carbon at 2%, "...converting agricultural land to forest in Alta and BC can account for more than 26% of Canada's Kyoto commitment" (p. 11). Although the expected Canadian target, in absolute terms, rose from 240Mt to 270 Mt since this study was published, the results are nonetheless hopeful. The authors even extrapolated the results to the entire country and depicted afforestation with hybrid poplar as having great potential to meet Canada's emissions target.

While accounting for different carbon pools, Van Kooten et al. (1999) also looked at the economics of afforestation for carbon sequestration purposes. In addition to carbon contained in saleable and non saleable timber volume, and soil carbon, the study considers wood products as a sink leaking at a slow decay rate. It is also assumed that part of the harvest (20%) is used as a substitute for coal in energy production thus displacing carbon emissions and earning the associated credits. The study was conducted

for the same region, and used similar cost estimates as Van Kooten et al. (2000) but this time assuming a 15 year rotation. The results indicate that afforestation in the region could fulfill up to 19.6% of Canada's commitment (always with respect to the 240Mt target).

However, in both studies the authors caution that the feasibility of large afforestation on private land within a short period of time and the potential need to discount physical carbon more heavily could change these results. First, whether or not to discount carbon credits depends on the path of marginal damages. If damages due to GHG concentration are constant over time then there should be no discounting since a reduction today would provide the same benefits as a reduction tomorrow. Yet, if a reduction today provides greater benefits due to the urgency of the situation then carbon credits should be discounted at a positive rate. This argument holds when looking at the problem from a social point of view (or a central planner standpoint). However, when studying project feasibility from an investor point of view, the argument becomes irrelevant and the factor of importance is the expectation about carbon price.

The feasibility of large scale afforestation within a short period was investigated by Van Kooten (2000). The study looked at the dynamics of tree planting for carbon sequestration purposes and relied on similar numbers and assumptions as in the previous work (i.e. same cost structure and the wood product sinks were included). However, a 12 year rotation was used instead of 15 years. As expected, the dynamics of afforestation showed that, for carbon prices ranging between \$10/tC to \$20/tC, afforestation of large

areas all at once is not economically optimal. The study estimates that when accounting for the dynamics of the process, only around 7% of the KP commitment could be fulfilled through an afforestation program which would target private land. Furthermore, Van Kooten (2000) outlines a series of potential barriers or costs that were left unaccounted for in the previous studies. Among the barriers mentioned were: transaction costs (monitoring, verification and contracting costs), uncertainty, environmental cost, and the difficulties in establishing proper incentives for private landowners. Some of these barriers may explain the differences between cost engineering and actual behavior estimated with econometric studies.

To shed light on some of the impediments to afforestation, Van Kooten et al. (2002) studied landowners' perception and willingness to afforest part of their land. Transaction costs were their focal point. Results show that, even when fully compensated for forgone revenues, less than 25% of respondents would be willing to plant large blocks of trees. One conclusion of the study is that "asset specificity, in the form of developed land and investments in tractors, combines and other assets specific to crop production, may be an obstacle to afforestation" p.571. The results also outline the unwillingness of farmers to enter contracts of longer duration than 15 years which indicate that hybrid poplar is expected to be preferred to other native species. Previous results of Van Kooten (2000) indicated that around 7% of the KP commitment could be met through afforestation, yet if only 25% of landowners are willing to plant trees, the total afforestation potential should be reduced. Hence, less than 7% of Canada's commitment (former target of

240Mt) could be met through afforestation of marginal agricultural land with hybrid poplar in Alta and B.C.

Van Kooten et al. (2000) extrapolated their results to the entire country, yet there is no evidence that other regions will show similar potential to western Canada. McKenney et al. (2004) used a spatial model to investigate the distribution of afforestation costs across Canada. Similarly to Van Kooten et al. (1999), this study included wood products and fuel substitution as carbon pools and sources of carbon credits. But in contrast, the study relied on a higher opportunity cost of land, higher establishment cost and also higher stumpage value than Van Kooten et al. (1999) and Van Kooten (2000). According to their study, under reasonable yields (i.e. less than $16\text{m}^3/\text{ha}\cdot\text{yr}$), the Prairie region is the most promising for afforestation while the potential in Eastern Canada is limited. Additionally, McKenney et al.'s (2004) results indicated a 12.7% land conversion rate in the prairies while Van Kooten et al. (1999) reported figures around 32%.

In the end, afforestation appears to be a viable option essentially in the Prairies. But even there, one may not expect much of the Canadian commitment to be fulfilled by this alternative when considering the willingness of farmers to participate and the dynamics of afforestation. Such a pessimistic conclusion puts an even greater emphasis on the importance of policy and institutional design related to the Offset System.

Beside the dynamic aspect of the afforestation process, the literature presented has highlighted two main sources of variation among studies; the carbon yield and the

presence of behavioral or individual preference factors in land conversion costs. In particular, the non-permanent nature of biosinks and the apparent unwillingness of some landowners to create biosinks on private land should be mentioned. The use of wood-products as a sink has been proposed to mitigate the impact of non-permanence on the economic feasibility of afforestation. However, this concept has yet to be accepted by the international community and it is debatable whether it will ever be recognized. The main problem being that once in the wood product pool, carbon becomes untraceable which poses a threat to environmental integrity. On the other hand, issues related to the presence of behavioral factors in individual decision making processes and landowners' reluctance to create carbon sinks has received little attention. Such factors should be explicitly taken into account in the policy design in order to obtain a well targeted and least-cost policy. As Van Kooten et al. (2002) stated this when discussing the potential for afforestation of marginal agricultural land:

"...the major obstacle will be to convince farmers to plant trees with the success of so doing dependent on the institutions and incentives to be used." (p. 568).

2.2 Theories of Farmers' Adoption Behavior

In the previous section, the value demanded by landowners to adopt BMPs and change land use was inclusive of individual decision making characteristics and preferences. Yet, these could not be properly defined. The following section is meant to clarify what factors influence the adoption behavior of farmers by investigating theories and empirical work applicable to farmers' adoption decisions.

First, farmers face an important decision concerning their participation in mitigation efforts as they are given the possibility to be compensated for their efforts. One tool that can help in making such a decision is the net present value formula (NPV) which is based on discounted expected revenues and costs related to new investments. Many cost of sequestration studies that have provided estimates of biosink potential were based on the assumption that investment/adoption decisions would follow such a rule. Those studies relied on pure profit maximizing principles including bottom-up and sectoral models.

However, the adoption and diffusion of technology seem to be far more complex than this simple rule. There exists a large body of literature which looks at adoption and diffusion of new technologies in the farming community. Although BMPs may not all represent new technologies per se, they generally represent new ways of doing things for most of the farming community. According to this literature, the factors affecting the diffusion process and the decision to adopt new technology can be divided into two groups: structural characteristics (such as farm size, ownership type, land quality, and human capital), and information related factors (for example: risk, learning, and education) (Diederer et al. 2003a).

Structural characteristics

Structural characteristics represent sources of heterogeneity among farmers and can explain why farmers may or may not adopt new technologies or practices. Empirical studies have found structural factors such as farm size and land quality to be significant determinants of adoption and technology diffusion (Sunding and Zilberman, 2001). In the

case of afforestation such factors as land attributes and climate can play an important role in the adoption process as they will influence the profitability of individual projects. An analysis of this aspect could provide information that would be useful to identify and target the most likely adopters. For example, Kort and Turnock (1999) found that black soils of the Prairie region were the most suitable for hybrid polar plantation. Nevertheless, the present study will limit itself to the targeting already done in previous research. In accordance with Van Kooten et al. (2000) and McKenney et al. (2004), the study will look at the afforestation of marginal agricultural land in western Canada. However, it will focus on information related factors, their links with public policies, and the issue of non-permanence.

Information factors

Mansfield (1961) was among the first to base his view of technology adoption and diffusion on information spread. He saw the diffusion process as one of imitation and used an epidemic diffusion model to explain it. His model was based on the assumption of a "bandwagon" effect; as other farmers in the neighborhood adopt the technology, one has the opportunity to gain precious information that will feed into his own decision process. Social scientists such as Rogers (1962) have also proposed geographic factors and distance as explanatory variables. Part of their reasoning was based on the fact that cost of acquiring information may be higher in remote regions.

The imitation and cost of information effect may be part of the behavioral aspect of decision making. Since afforestation is not a widespread alternative to other crops such as

forage or grains, farmers may not be inclined to switch land use, in part due to a lack of information. In this regard, all of the information and publicity around climate change issues and the Kyoto Protocol may help to reduce this barrier. Information diffusion is an important part of a successful afforestation program, yet information from peers and neighbors concerning their experience with afforestation projects may still be lacking.

Another important factor related to information is risk. A recent review of the literature on risk and farmers' adoption processes by Marra et al. (2003), conclude that:

"[r]elatively recent research about the role of risk, uncertainty and learning in the adoption of agricultural technologies has finally provided compelling support for the long held and often stated view that adoption processes are strongly affected by risk-related issues"(p.231).

They further comment that most relevant aspects of risk in the adoption process are:

- farmers' perception of risk associated with the technology
- farmers' risk attitudes
- the role of learning in adoption decisions
- the value of an option to delay adoption

As well, Pagano (1993) referred to signal detection theory to summarize the role that information plays in the decision making process. This theory, which stems from experimental psychology, states that there are three ways to enhance signal detection; strengthen the signal, reduce background noise, or improve the detector's skills. In terms of policy aimed at inducing the adoption of BMPs, the signal to be sent is the information about beneficial attributes of the BMPs (i.e. information diffusion), the detector's skill is

the management ability of the farmer which allows him to detect a profitable venture (i.e. learning, experience, and education), and finally the background noise is the misinformation or uncertainty about beneficial attributes of BMPs (i.e. risk).

2.3 Empirical Literature on Barriers to Adoption

Theory suggests that information access, risk attitude, and the presence of an option to delay adoption may be important determinants in investment decision making and therefore could explain the gap between the cost of sequestration obtained with cost engineering and econometric analysis. The empirical literature on land-use change can also provide helpful insights in identifying the factors creating this gap.

Parks and Hardie (1995) acknowledge in their study that given the presence of friction in land use change, the assumed opportunity cost of land (rental cost) could be underestimated. Parks (1995) using a dynamic model of land use decision making at the agricultural and forestry margin explains the presence of seemingly irrational land use decision as the result of the existence of risk and capital gain expectations. Likewise, Stavins and Jaffe (1990) recognized the presence of friction in land use change, which they attribute to: "forest age distribution, liquidity constraints, uncertainty about permanence of price movements, and decision-making inertia" (p.343). As well, Schneider (2002) mentions that "Disadvantages of MP [mathematical programming] models include the tendency toward extreme, purely profit-based specialization. Often omitted in large MP models are so-called option values..." (p.9). And finally, the idea that

uncertainty in returns may create a barrier to investment is also found in the afforestation literature:

“The lack of annual cash flow and unpredictable markets have been the biggest obstacles to wider farmer participation...” p.33

Stanton et al., 2002

Stavins (1999) identifies four factors that may induce a land use change premium: 1) real option due to irreversibility, 2) non-pecuniary returns, 3) liquidity constraints, and 4) "private or market benefits or costs of alternative land uses of which an analyst is unaware" (p.995). Using an econometric model to analyze land use change in the Delta states of the US, Stavins (1999) illustrated that sequestration costs obtained from "least cost" analyses would tend to underestimate real sequestration costs. However, his study did not identify which of the proposed causes was most likely creating the presence of the premium.

Kurkalova et al. (2003) measured the premium of conservation tillage adoption based on observed behavior. An adoption model was used with data from the National Resource Inventory (NRI) of Iowa farmers for the 1992 growing season. The model enabled them to quantify the premium and came up with estimates of \$2.40/acre·yr for corn and \$3.30/ac·yr for soybean. But, in contrast to Stavins (1999) only two potential causes are suggested: 1) option value due to irreversibility, and 2) farmers' risk aversion combined with increased risk due to the new practices. This study also lends support to the existence of an adoption premium. In consequence, a subsidy over and above the least-

cost analysis estimates would be needed to provide farmers with the appropriate incentives to create carbon sinks.

Additionally, Schatzki (2003) found the existence of a real option value on land use change from agriculture to forestry. His study used data from the Conservation Reserve Program (CRP) in Georgia, in combination with a real option model. When testing the implications of the real option model with data from the CRP program, the study fails to reject the presence of real options. Hence, the study first confirms the presence of a premium over the least-cost estimates and moreover associates such a premium to the real option hypothesis.

To summarize, the potential barriers to the adoption of BMPs may have many sources. One explanation is that the wedge between least-cost estimates may be due to non-pecuniary values. This could take the form of a value attributed to the way of life that agriculture provides. Such social value is rather hard to assess and quantify and most importantly public policies may not be able to affect such a value within a limited time frame. The other main determinants of land use decisions cited in the literature consist of risk related factors. This observation should come as no surprise given that farming is perceived as a business facing a large number of risks. The impacts of risk aversion as well as the presence of a real option value are mentioned by most authors. In addition, there are some empirical indications that real options are part of the premium value.

Consequently, it seems important to understand the kind of risks carbon sink project developers will be facing. The impact of risk factors should be evaluated to estimate the potential response of farmers to various incentive schemes and to develop a well targeted and least cost carbon sequestration policy. Given the growing evidence of real option existence and the ability of short term public policy to influence the magnitude of such a value by offering risk management tools, long term contracts and/or subsidized investment in the early stages of the project, the presence of such a value and its relation to public institutions are investigated.

2.4 Real Option Theory

An important body of literature has developed the theory and the application of real options (McDonald and Siegel 1986, Dixit and Pindyck 1994, Trigeorgis 2001). Under conditions of uncertain returns and investment irreversibility, real options stem from the opportunity of delaying the investment decision in order to gain information. Waiting can provide an opportunity to catch the upside swing of the market while allowing enough flexibility to avoid a loss associated with a future market downturn. Hence, postponing the decision provides managers with flexibility that allows them to deal with uncertainty. Dixit and Pindyck (1994) provide evidence that uncertainty combined with irreversibility has a negative impact on investment under risk neutrality conditions.

To put it in context, let us compare real option theory to the NPV formula, which is the traditional and most widespread capital budgeting technique. The NPV formula is a static analysis which consists of discounting all expected future costs and benefits from the project and summing them over the investment lifespan. If the sum is greater than the

initial investment cost the project is deemed to be profitable and should be undertaken. The investment threshold corresponds to an NPV equal to the investment cost and is usually referred to as the Marshallian trigger.

The NPV methodology is quite flexible and can be adjusted for inflation or growth in returns. The calculation can also account for risk preferences of the investor and risk level of an investment by adjusting the discount rate. However, it only provides deterministic point estimates and does not account for the dynamic aspects of decisions. Most critiques of the NPV methodology concern the implicit assumption of a now or never type of decision, i.e. not investing today means never investing at all. A second criticism puts in doubt the validity of assuming that the investment is fully reversible at no cost as is inherent in the NPV approach. As McDonald and Siegel (1986) pointed out, in the case of an irreversible investment the two options to invest or not to invest are asymmetric since the decision of delaying the investment can be reversed, although current revenues are forgone, but disinvestment in the case of an economic downturn is impossible.

In reality decision makers have, in most cases, the option to delay the decision and gain market information while at the same time investments are rarely freely reversible. Hence, in such cases the value of waiting one more period to gain information has to be weighted against the forgone revenues that an implemented project would generate. Real option theory has developed a framework to account for the risk and irreversibility involved in the decision process. By accounting for the dynamic aspects of the decision

process, real option theory gives value to the current lack of information (risk) and the flow of information accruing over time.

Real options unveil a barrier to investment since the investment trigger found using this approach (H) is usually higher than the Marshallian trigger (M) (see figure 2.1). This impediment to investment is explained in the literature by the fact that investing means "killing" the option to wait. And, alike any other option which always has a nonnegative value, an option to wait must be valuable as long as the project can turn out to be unprofitable in the future with some positive probability. In figure 2.1, the line c-c' reflects the value of investment (V) in function of periodic returns R as calculated from the NPV formula⁸. The Marshallian trigger is given by M, where the cost of the investment equals the sum of expected returns. However the value of the option to wait is given by the curve d-d'⁹. Since the option provides the right but not the obligation to implement the project, the value of the option to wait is nonnegative and increases with revenues of the underlying asset. At point M, it is clear that waiting has more value than investing. In fact the investment should be undertaken only at point H where the NPV of investment is as valuable as the option to wait.

The value of the option and the threshold H can be derived either by dynamic programming or by contingent claim analysis. Both methods lead to equivalent results but rely on different assumptions. The latter approach relies on a no-arbitrage condition and the existence of a portfolio which can replicate or span the investment project revenues

⁸ $NPV = [R/r] - I$, where r is the discount rate and I is the investment cost

and risks. This methodology requires the presence of a complete market¹⁰ in order to create the portfolio which properly duplicates the investment opportunity, yet carbon sequestration projects cannot be valued in such a way since complete markets do not exist at this time.

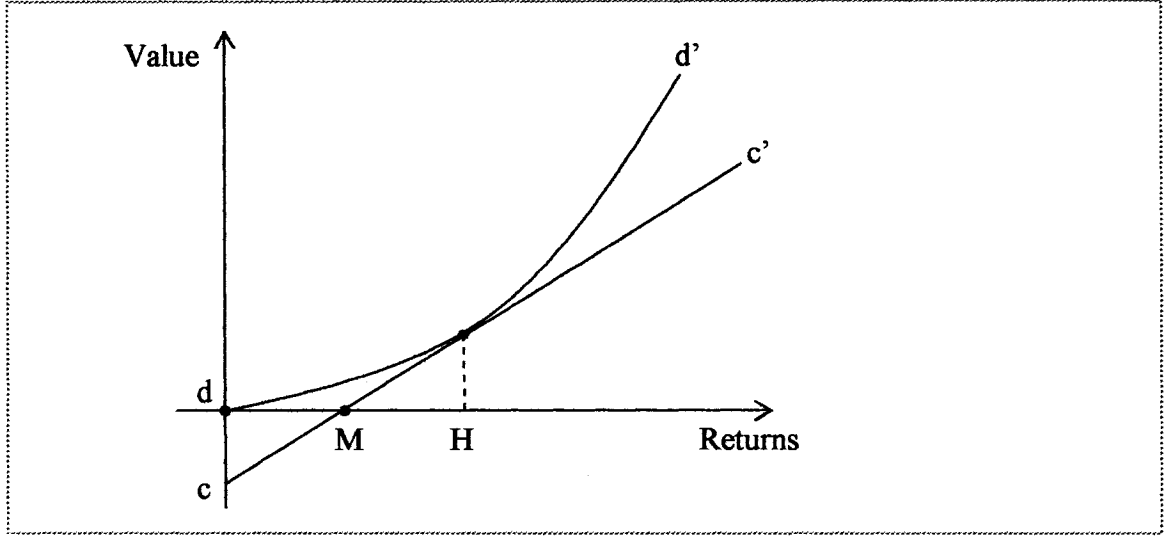


Figure 2.1: Investment threshold under NPV and real option approaches

Consequently, the dynamic programming approach must be used for the present case study. This approach starts with a Bellman equation (equation 2.1) stating that the optimal choice maximizes the sum of current profit flow and future value.

$$F_t(x_t) = \max_{\mu_t} \left\{ \pi_t(x_t, \mu_t) + e^{-r} E[F_{t+1}(x_{t+1})] \right\} \quad (2.1)$$

⁹ The value of the option is given by BR^β , where B is a constant and $\beta > 1$ is a root of the fundamental quadratic. (Dixit and Pindyck 1994, p.142)

¹⁰ A complete market is one in which every possible future state or payoff can be constructed from existing assets. Hence, it allows one to construct a portfolio that can exactly replicate the project payoff.

Where x , the state variable, could represent price, cost, or net revenues, and μ represents the investment decision to be taken¹¹. If we assume a binary choice between investment or the status quo, then we can differentiate between the investment region where $F_t(x_t)$ would be maximized by investment and the continuation region where $F_t(x_t)$ is maximized by the status quo. By algebraic manipulation, the following Bellman equation can define the equilibrium condition over the continuation region.

$$rF_t(x_t) = \pi_t(x_t) + E[dF] \quad (2.2)$$

This equation states that over the continuation region, where investing is not optimal, the owner of the asset commands a rate of return “ r ” to keep holding the asset. In equilibrium this rate must equal the flow of instantaneous returns plus expected capital gains. The value of the option to implement a project at a future date is embedded in the term $E[dF]$ which therefore contains more than the sum of changes in expected returns.

To properly account for the stochastic nature of x , the Bellman equation is expanded by deriving $E[dF]$ with Ito’s lemma which yields a partial differential equation which has to be solved using the value-matching and the smooth-pasting condition. The former condition states that at the threshold value, where the continuation and investment region meet, the value of the asset must be the same in both states, and the latter condition requires the investment and continuation region to meet tangentially¹².

¹¹ μ could be continuous if for example a level of input has to be chosen, or binary if we have to choose to buy an asset or not

The modified trigger (H) is then found to take the following form:

$$H = \frac{\beta}{\beta - 1} \cdot I \cdot r$$

With the NPV rule, the growth rate of an investment (μ) and the discount rate (r) are important determinants of the investment decision. However, their impact is different than under the NPV rule. In a real option model, an increase in the discount rate will create two opposite effects; it will reduce the value of future returns, but this decrease will be dampened since the importance given to the uncertainty of those returns is also reduced. Yet, as with the NPV rule, a higher interest rate will lead to less investment. But in contrast to the NPV threshold, a lower drift rate (μ) will produce a higher value for parameter β and the threshold H will decrease. It occurs because of the reduced appreciation rate of investment, hence if one invests it should be done earlier than later, and waiting becomes costlier.

As was outlined before, the key feature of the real option methodology is its ability to account for risk. Accordingly, the parameter β is found to be a function of the return's variance (σ^2). Given a higher level of variance (σ^2), β decreases, which results in a higher threshold and less investment. Explanations come from the greater possibility of a loss in future periods which increases the value of waiting. In short, higher return volatility leads to a higher option value which increases the barrier to investment by increasing the current value of the underlying asset.

¹² See Dixit and Pindyck (1994) p.131 for a discussion of the optimality characteristics of these conditions.

An important consequence of the existence of a real option is market friction and stickiness. For example, Dixit and Pindyck (1994) show the entry and exit price thresholds, P_H and P_L respectively, in the presence of real option values (see figure 2.2). Under classical economic rules, the firm's entry-exit threshold should be at C which represents operating costs. However, real options create a wedge between the two thresholds inducing some stickiness in the decision making process. This gap between entry and exit threshold is found to increase with the return's variance (σ^2), sunk costs, and operating costs.

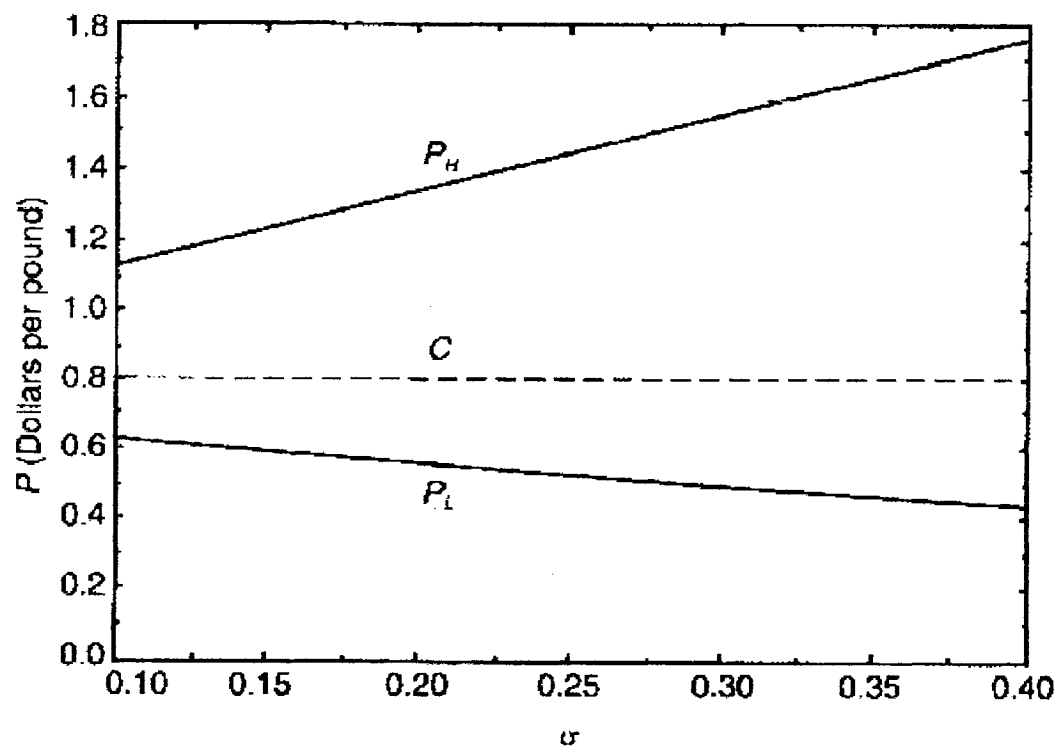


Figure 2.2 : Entry and exit thresholds as functions of return's volatility (σ)
Source: Dixit and Pindyck (1994), p.226

The real option approach has its limitations. Much like standard capital budgeting techniques, the investment threshold is sensitive to the discount rate which is chosen

more or less arbitrarily when using dynamic programming. Most researchers have addressed this weakness by performing sensitivity analysis with respect to the discount rate. Yet, the main limitation of real option modeling is the need to solve partial differential equations (PDE) which can be quite complex and sometimes solvable only with numerical methods. The complexity of the PDE is linked to the diffusion process used to depict the evolution of prices, revenues or costs over time. The most popular diffusion process is the Geometric Brownian Motion (GBM). The advantage of such a process is the simplicity of the resulting PDE which makes for a simple and tractable model.

Beside its pragmatic aspects, GBM can also be justified on theoretical grounds due to its consistency with the efficient market hypothesis which states that current prices should fully reflect past information since markets should respond immediately to new information. As a result, the analysis of past price behavior should be of no use in predicting future prices, as is the case for GBM.

Despite its popularity in modeling stock prices, GBM has been criticized when used to depict the behavior of commodity prices. The basic theoretical argument is that supply response should prevent the price from wandering too far from the long run equilibrium. For this reason, price should be bounded above, which is not the case for the GBM. To account for the supply response effect many have proposed the use of a Mean Reverting Processes (MR), which in contrast to GBM are stationary around a long-term trend. These critics have been supported by the empirical work of Wang and Tomek (2004) who

studied the behavior of different commodity prices by performing various types of unit root tests. Their work supports the use of MR processes as being a better approximation of commodity price behavior.

However, the use of MR processes makes the analysis of real options quite complex and it is questionable whether the additional benefit of using an MR outweighs the complexity cost. Metcalf and Hassett (1995) used a Monte Carlo simulation to study the behavior of real option investment thresholds found under two different assumptions; a price diffusion following a GBM or following a Geometric Mean Reverting Processes (GMR). The former is a non-stationary process while the latter is stationary. An important difference between the two is the time dependent variance of non-stationary processes which grows with time and tends to infinity. On the other hand, the variance of stationary processes converges to a finite constant. Therefore, the impact of variance in the model developed under the assumption of non-stationarity will be much greater than if the model was developed under the assumption of stationarity. This is what Metcalf and Hassett (1995) called the “*variance effect*”. Since the investment thresholds found with real option models are increasing in volatility, the thresholds found under the GBM assumption will be biased upward if the true data generating process is closer to a GMR.

However, one of their interesting findings is that if one replaces the threshold with the cumulative investment over a given time period, the misspecification impact of modeling a GBM, while a GMR is seen as a better approximation, is greatly reduced. This originates from what they called the “*realized price effect*” which refers to the larger

probability of reaching a higher value for a non-stationary process compared to a stationary process. Thus, for the GBM even if the investment threshold is greater, the probability of investing within a given period is almost the same. In fact under certain conditions the probability of investment is found to be higher when using a non-stationary process.

“The average level of cumulative investment at the end of a finite period is essentially the same under either GBM [non-stationarity] or GMR [stationarity]”

Metcalf and Hassett (1995), p.148.

Empirical literature on Real Options

Although the theory of real options is relatively recent its applications are numerous. Price and Wetzstein (1999) used it to investigate optimal entry and exit in peach orchard operations. They found the entry trigger to be around 2.2 times higher with real option than NPV. Real option theory has also been used in combination with econometric models (usually logit models) to explain past investment behavior. Diederer et al. (2003b) estimated a hurdle rate of 1.73 times the NPV threshold and found the adoption of energy-saving technology in Dutch greenhouses to be more consistent with the prediction of a real option model than with NPV methodology. Similarly, Schatzki (2003) found land-use change decisions between forestry and agriculture supportive of real option theory.

In addition, real option models have been employed to assess the design of public policies. Carey and Zilberman (2002) studied the impact of water markets on the

adoption of irrigation technology. They found the investment threshold under the real option approach (H) to be more than twice the Marshallian trigger (M) and found that water markets could delay adoption on farms with scarce water supply. Winter-Nelson and Amegbeto (1998) used on a real option model to estimate market liberalization impacts on the adoption of soil and water conservation practices in developing countries. Through simulations, they analyzed the incentives under various scenarios to find that in the absence of institutions to dampen price movement, market liberalization could have an adverse effect on welfare and the environment. Finally, Khanna et al. (2000) studied investment in site-specific crop management using real option modeling and numerical simulation. An adoption delay of at least 3 years was found to be optimal for most farms and in order to trigger immediate investment the cost-share subsidy would need to be substantially higher than NPV would suggest.

In summary, theoretical and empirical work show that a significant barrier to investment exists in the presence of uncertainty and irreversibility. Such a barrier could command revenues to be as high as two or three times what would be required under a NPV approach. The farming community seems to be no exception to this rule. Hence promoting the adoption of BMPs involving risks and sunk cost, as is the case for afforestation, will be a difficult task and the public policy design has to account for the presence of risk and sunk cost to be successful.

2.5 Carbon Accounting: Addressing Non-Permanence

As was mentioned in the introduction, the issue of non-permanence, which relates to the risk of sequestration reversal, is what differentiates carbon sink emission removal from

avoided fossil fuel emissions. As a result, biosink uncertainty creates a threat to the environmental integrity of the offset system. Hence there is a need to monitor the sinks and assign liability to ensure that a maintenance effort will be continuously provided. The key here is that there is greater control on release date of fossil fuel carbon and a lack of control in the case of biomass carbon sequestration.

To account for the difference between the two types of mitigation effort that are reductions (avoided emissions) and removals (sequestered carbon) a few accounting schemes have been proposed.

1) TCs, tCERs and Rental Approaches

The idea of temporary credits (TCs) or temporary certified emission reduction (tCER) was first proposed by Colombia (2000). The tCER accounting approach consists of granting temporary credits that would be valid only over a predetermined period after which the buyer would have to replace them with either new tCER or permanent credits (ERUs or their equivalent). The purpose of this approach was to eliminate the perpetual liability link with the issuance of permanent credits from land use, land use change, and forestry (LULUCF) projects. Developing countries like Colombia were concerned that the liability rule linked with the issuance of permanent credits could infringe on their sovereignty since land enrolled in the program could no longer be diverted to serve other development objectives.

To provide a more flexible framework, the Colombian proposition was based on a crediting period of one year. Later in 2002, another version, the 5 year life span tCERs or

tCER5, was proposed by the European Community (UNFCCC, 2002). The purpose of this second version was to reduce transaction costs related to verification and get the expiration of tCERs to coincide with the commitment period. But this scheme exposes the parties involved to a potential reversal during the 5 year period which creates a need for insurance and risk management schemes. Most importantly, although tCER5 contribute to a reduction in the transaction cost, they also reduce economic efficiency of the program as it delays the returns to project owners. The carbon sequestered during the crediting periods is not given any returns until the next commitment period, thus the return to carbon can be delayed up to 5 years. The net effect of extending the crediting period to 5 years depends on the cost of monitoring and verifying projects and the forgone benefits due to late entry of some carbon in the accounting system. Yet, the actual policy design appears to put more emphasis on the need for a flexible system and TCs of 1 year duration seem to be the preferred alternative.

With temporary credits, services are only rented for a limited period of time, and the value of such credits must be discounted compared to a permanent emission reduction. Chomitz (2000) proposed that the minimum value of tCERs should reflect the difference between the actual permanent credit value and the discounted expected value at tCER expiry date.

$$tCER = ERU_0 - E[ERU_t]/(1+r)^t$$

Values of TCs computed using this approach and with different discount rates are given in Table 2.1. In consequence, the value of carbon sequestration becomes highly dependent on the time value of money and the expectation of future carbon price. Such a

discounted value may prove to be insufficient to get landowners to participate in a mitigation effort unless the flexibility that it provides has enough value to offset the discounting effect. In addition, buyers may not be strongly attracted to TCs as they are left with a liability upon expiration.

Table 2.1: Value of TCs given a value of \$15 and \$25 for permanent credits

Discount rate	TC value (ERU=\$15)	TC value (ERU=\$25)
2%	\$0.29	\$0.49
4%	\$0.58	\$0.96
8%	\$1.11	\$1.85

2) Offset Credits (OCs) and Required Replacement

A required replacement scheme is advantageous as it provides credits that are fully fungible with the rest of the market, i.e. they are considered as permanent credits. The question of non-permanence is addressed through liability rules. After certification of the credits, the project owners assume the liability for any reversal of the sequestration process and to ensure environmental integrity project owners may be required to insure against reversal to prevent the risk of defaulting. As buying insurance may be hard to do during the first commitment period, the establishment of carbon reserves may also serve as risk management tools.

Hence by using this approach, sequestration credits would be given the same value as reduction credits like ERUs and thus, buyers are likely to prefer this alternative.

However, an important issue is to decide on the period over which the carbon must remain sequestered, namely the liability period. Deciding on a minimum sequestration period is likely to be a political decision as reversal occurring after the liability period would be counted as a debit against the Canadian government inventory. Hence, a short period could become costly for the government whereas economic feasibility will be sacrificed if the period is too long. In this study, one scenario involving the required replacement approach is considered. However, assuming that liability periods are of 20 years or more and given the short rotation period of 12 years, the length of liability period becomes irrelevant in the present case study.

2.6 Agroforestry and Hybrid Poplar

Hybrid poplar was first developed as an energy crop during the oil crisis of the 1970s. However, it turned out to be grown mainly as a source of fiber material for the pulp and paper industry. The lumber industry's by-products were the main source of supply for paper mills which were then subject to the cyclical demand for housing and construction material. Growing hybrid poplar was mainly undertaken by the forest industry as it became a solution to mitigate against the impact of supply shocks. More recently, uses of hybrid poplar have been extended to building products such as oriented strand board (OSB), and environmental uses such as waste water treatment, and carbon sequestration. In addition, when grown on farms hybrid poplar can provide added benefits like crop diversification and a reduction in soil erosion (AAFC, 2001).

The rotation length of hybrid poplar depends on the climatic conditions, land attributes, and also the intensity of management. Depending on these factors the rotation length of a

plantation may vary from 6 to over 20 years. Intensive management, which includes fertilization, pesticide application and weeding, will reduce the time needed to reach maturity. Short rotations, less than 10 years, require intensive management and will result mainly in pulpwood production. On the other hand, longer rotation lengths, 12 to 15 years, are required to produce sawlogs and peeler logs (Stanton et al. 2002).

For productive growth, poplars require moist and well drained sites, although they can tolerate periodic flooding. It is reported that the best sites have over 400mm of annual precipitation. The ideal soils are loams which offer reasonable drainage, abundant nutrients, and a pH between 5.5 and 8 (AAFC, 2001). According to Kort and Turnock (1999), the best suited soils in Saskatchewan would be black soils followed by dark brown soils. The Saskatchewan Forest center used a yield of 100m³/ha to 200m³/ha for a 20 year plantation. To represent hybrid poplar growth, Van Kooten et al. (2000) used a Chapman-Richards growth curve as depicted in figure 2.3.

The establishment of hybrid poplar is a long term investment and total establishment cost estimates vary from \$1200 to over \$2500 per hectare. Typical cost distributions over rotation periods of 12 and 20 years are given in figure 2.4. The bulk of the costs are made up of planting stock, pruning, and weed and pest management during the first years of establishment. In later years, the main costs include machinery depreciation, maintenance cost, property taxes and some fertilizer applications when the crop is managed intensively.

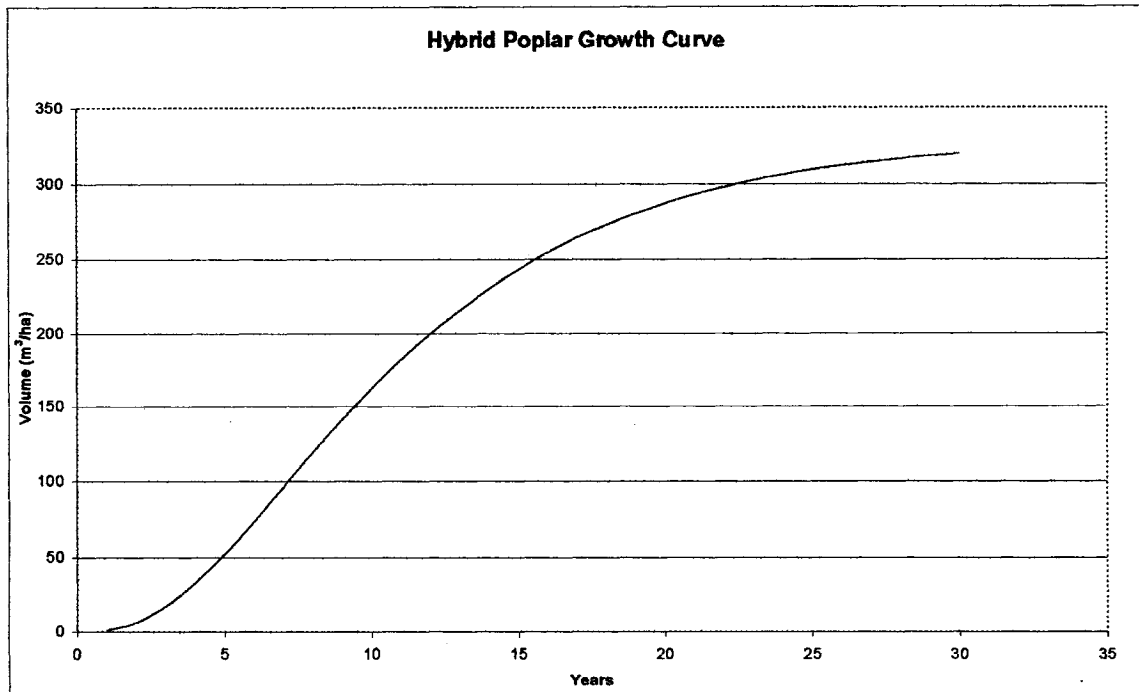


Figure 2.3: Chapman-Richards growth curve for hybrid poplar in Boreal regions. Van Kooten et al. 2000

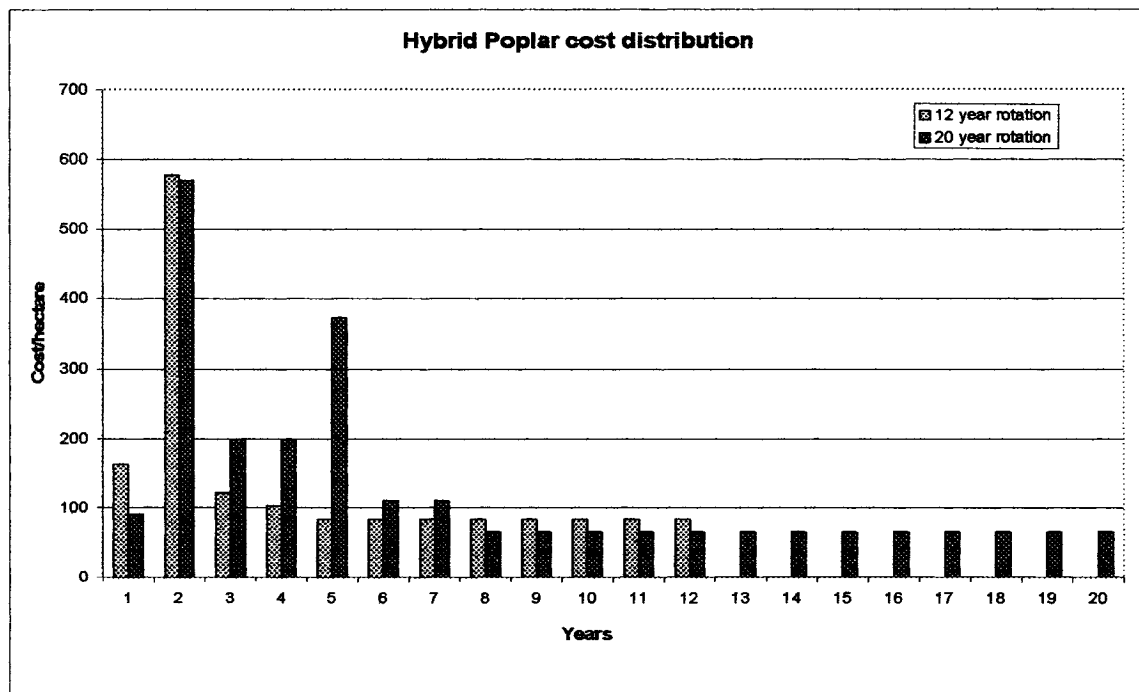


Figure 2.4: Hybrid Poplar cost distribution
 Sources: 12 year rotation - Kiecker and Schoessow (2000), University of Wisconsin-Extension
 20 year rotation - Saskatchewan Forest Center, Agroforestry unit, May 2003.

Chapter 3: Model

In this section two real option models are developed so as to better approximate the land use decision under various scenarios. The basic model includes volatility of forestry revenues and assumes that the project is irreversible. This model is meant to represent the situation at the no rent margin where agricultural revenues should have no impact on the decision to afforest for carbon credits. The model is extended to include the liability scheme of OCs. To estimate the impact of a carbon market on afforestation incentives on productive agricultural land, a second model is developed that includes agricultural revenue uncertainty and allows for reversibility of the project.

3.1 Model 1

Let $V^a(\cdot)$ be the value of land that entitles the owner to a flow of net revenues R_a and, at the same time, the opportunity to invest in an afforestation project. The implemented afforestation project would yield a net revenue R_f per year, and it costs C^f to establish a new plantation every 12 years. Revenues related to an afforestation project will be lumpy in practice. However, for the present purpose it is assumed that the annualized rent (R_f) is equivalent to the discounted sum of the lumpy returns. By this simplification, the inconvenience and constraints related to the lumpy nature of returns is omitted and as a result the decision rule obtained should tend to favor investment more than would really occur.

The owner is assumed to maximize the value of their asset by solving:

$$V^{a,t}(R_{f,t}) = \max \left(R_a + \frac{V^{a,t+1}}{1+r}, R_{f,t} - C^f + \frac{V^{f,t+1}}{1+r} \right)$$

By assumption, C^f and R_a are constant and R_f follows a geometric Brownian motion with drift μ_f and volatility σ_f

$$\begin{aligned} dR_f &= R_f \mu_f dt + R_f \sigma_f dz \\ dz &= \varepsilon_{f,t} \sqrt{dt} \end{aligned}$$

where ε_f are error terms distributed normally [$\sim N(0,1)$].

The optimal switching rule can be found by solving the problem using dynamic programming. The following Bellman equation states that over the continuation region, where investing is not optimal, the owner of the asset commands a rate of return “ r ” to keep holding the asset. At equilibrium, this rate must equal the flow of instantaneous returns plus expected capital gains.

$$rV^a = E(R_a + dV^a)$$

Expanding by Ito’s lemma

$$\begin{aligned} E(dV^a) &= E[V_f^a dR_f + \frac{1}{2} V_{ff}^a dR_f^2] \\ E(dV^a) &= V_f^a R_f \mu_f dt + \frac{1}{2} \sigma_f^2 R_f^2 V_{ff}^a dt \end{aligned}$$

the Bellman equation can be written as:

$$rV^a = R_a + V_f^a R_f \mu_f dt + \frac{1}{2} \sigma_f^2 R_f^2 V_{ff}^a dt$$

leading to the following solution

$$V^a = GR_f^\beta + HR_f^\alpha + \frac{R_a}{r}$$

where G and H are constants to be determined later. β (>1) and α (<0) are the roots of the fundamental quadratic equation (Dixit and Pindyck 1994, p.142).

$$\beta = \left(\frac{1}{2}\sigma_f^2 - \mu_f + \sqrt{\left(\mu_f - \frac{1}{2}\sigma_f^2 \right)^2 + 2\sigma_f^2 r} \right) \cdot \sigma_f^{-2} > 1$$

$$\alpha = \left(\frac{1}{2}\sigma_f^2 - \mu_f - \sqrt{\left(\mu_f - \frac{1}{2}\sigma_f^2 \right)^2 + 2\sigma_f^2 r} \right) \cdot \sigma_f^{-2} < 0$$

The boundary condition implies that as R_f tends to zero the value of the option to implement the project should tend to zero as well. Therefore, since α is negative, H must be set equal to zero. The final solution is then:

$$V^a = GR_f^\beta + \frac{R_a}{r}$$

If it is assumed that investment is irreversible, the value of land in forestry must equal its expected present value

$$V^f = \frac{R_{f,t}}{r - u_f} - \frac{K}{r}$$

where the last term represents, as an annuity equivalent, the planting, and establishment costs of future rotations.

The value matching condition

$$GR_f^\beta + \frac{R_a}{r} = \left(\frac{R_{f,t}}{r - u_f} - \frac{K}{r} \right) - C^f \quad (3.1)$$

states that at the point of conversion to forestry, the value of land in forestry net of all conversion cost must equal the value of land in agriculture.

The smooth pasting condition

$$\beta GR_f^{\beta-1} = \frac{1}{r - \mu_f} \quad (3.2)$$

states that at the threshold, the value of land in both uses must meet tangentially with respect to R_f . Dixit and Pindyck 1994, p.130, provide arguments showing the necessity to satisfy this condition in order to obtain an optimal solution.

Solving equation 3.1 and 3.2 the optimal switching rule is found to be

$$\bar{R}_F = (r - \mu_f) \frac{\beta}{\beta - 1} \left(\frac{K}{r} + \frac{R_a}{r} \right) \quad (3.3)$$

This can be compared to the classical decision rule under the net present value calculation.

$$NPV \rightarrow \bar{R}_{F,NPV} = (r - \mu_f) \left(\frac{R_a}{r} + C^f + \frac{K}{r} \right)$$

The difference lies in the factor $\frac{\beta}{\beta - 1}$ which is dependent on the volatility and drift parameters of the diffusion process. And since β is larger than 1 this real option factor is necessarily positive and larger than 1. The investment threshold is increasing in C^f and in R_a . As well, it is decreasing in ρ , μ_f , and increasing in r and μ_a .

Model 1a: Including an uncertain liability cost

An uncertain liability cost L is introduced to accommodate carbon accounting rules under OCs. As with the revenues related to an afforestation project, liability cost will be lumpy in practice. However, for the present purpose it is assumed that an annualized cost (L) equivalent to the discounted sum of the lumpy costs.

As before, the owner is assumed to maximize the value of their asset by solving

$$V^{a,t}(R_{f,t}, L_t) = \max \left(R_a + \frac{V^{a,t+1}}{1+r}, R_{f,t} - L_t - C^f + \frac{V^{f,t+1}}{1+r} \right)$$

It is assumed that C^f and R_a are constant and that each of R_f and L follow a geometric Brownian motion with drift μ_i and volatility σ_i

$$dR_i = R_i \mu_i dt + R_i \sigma_i dz$$

$$dz = \varepsilon_{f,t} \sqrt{dt}$$

$$dL = L \mu_l dt + L \sigma_l dz$$

$$dz = \varepsilon_{l,t} \sqrt{dt}$$

where ε_i are error terms distributed normally [$\sim N(0,1)$] and $E[\varepsilon_l \varepsilon_f] = \rho$ is the correlation coefficient between L and R_f which is expected to be positive since the liability cost and a portion of forestry revenues are both a function of carbon price. Although the added uncertainty related to the liability should reduce investment incentives, this positive correlation should dampen the effect.

The Bellman equation is then

$$rV^a = E(R_a + dV^a)$$

Expanding by Ito's lemma

$$E(dV^a) = E[V_f^a dR_f + V_l^a dL + V_{l,f}^a dL dR_f + \frac{1}{2} V_{ll}^a dL^2 + \frac{1}{2} V_{ff}^a dR_f^2]$$

$$E(dV^a) = V_l^a L \mu_l dt + V_f^a R_f \mu_f dt + \rho_{f,l} \sigma_l \sigma_f L R_f V_{l,f}^a dt + \frac{1}{2} \sigma_l^2 L^2 V_{ll}^a dt + \frac{1}{2} \sigma_f^2 R_f^2 V_{ff}^a dt$$

the Bellman equation can be written as

$$rV^a = R_a + V_l^a L \mu_l dt + V_f^a R_f \mu_f dt + \rho_{f,l} \sigma_l \sigma_f L R_f V_{l,f}^a dt + \frac{1}{2} \sigma_l^2 L^2 V_{ll}^a dt + \frac{1}{2} \sigma_f^2 R_f^2 V_{ff}^a dt$$

To make this partial differential equation more manageable, let $V^a(R_f, L) = L v(R_f/L)$

Then:

$$V_f^a = v'(R_f / L)$$

$$V_l^a = v - \frac{R_f}{L} v'(R_f / L)$$

$$V_{ff}^a = v''(R_f / L) \frac{1}{L}$$

$$V_{ll}^a = \left(\frac{R_f}{L} \right)^2 v''(R_f / L) \frac{1}{L}$$

$$V_{lf}^a = -\frac{R_f}{L} v''(R_f / L) \frac{1}{L}$$

and

$$E(dV^a) = \left(v - \frac{R_f}{L} v' \right) L \mu_l dt + v' R_f \mu_f dt + \rho \sigma_l \sigma_f L R_f \left(-\frac{R_f}{L} \cdot \frac{1}{L} v'' \right) dt$$

$$+ \frac{1}{2} \sigma_l^2 L^2 \left(\left(\frac{R_f}{L} \right)^2 \cdot \frac{1}{L} v'' \right) dt + \frac{1}{2} \sigma_f^2 R_f^2 \left(\frac{1}{L} v'' \right) dt$$

The Bellman equation can then be written as

$$rLv = L + \left(v - \frac{R_f}{L} v' \right) L \mu_i dt + v' R_f \mu_f dt + \rho \sigma_i \sigma_f L R_f \left(-\frac{R_f}{L} \cdot \frac{1}{L} v'' \right) dt \\ + \frac{1}{2} \sigma_i^2 L^2 \left(\left(\frac{R_f}{L} \right)^2 \cdot \frac{1}{L} v'' \right) dt + \frac{1}{2} \sigma_f^2 R_f^2 \left(\frac{1}{L} v'' \right) dt$$

Dividing through by L and collecting like terms gives the following solution:

$$rv = 1 + \left(v - \frac{R_f}{L} v' \right) \mu_i dt + \frac{R_f}{L} v' \mu_f dt - \rho \sigma_i \sigma_f \left(\frac{R_f}{L} \right)^2 v'' dt \\ + \frac{1}{2} \sigma_i^2 \left(\frac{R_f}{L} \right)^2 v'' dt + \frac{1}{2} \sigma_f^2 \left(\frac{R_f}{L} \right)^2 v'' dt \\ 0 = 1 + v(\mu_i - r) + Rv'(\mu_f - \mu_i) + R^2 v'' \cdot \frac{1}{2} (\sigma_i^2 + \sigma_f^2 - 2\rho \sigma_i \sigma_f)$$

where the last line uses the substitution $R = R_f/L$. Thus, it provides a simple differential equation whose solution is:

$$v = WR^\theta + ZR^\delta + \frac{R_a}{rL}$$

or

$$V^a = WR_f^\theta L^{1-\theta} + ZR_f^\delta L^{1-\delta} + \frac{R_a}{r}$$

where W and Z are constants to be determined later. $\Theta (>1)$ and $\delta (<0)$ are the roots of the fundamental quadratic equation (Dixit and Pindyck 1994, p.142).

$$\theta = \left(\frac{1}{2} \sigma^2 - \mu + \sqrt{\left(\mu - \frac{1}{2} \sigma^2 \right)^2 + 2\sigma^2(r - \mu_i)} \right) \cdot \sigma^{-2} > 1 \\ \delta = \left(\frac{1}{2} \sigma^2 - \mu - \sqrt{\left(\mu - \frac{1}{2} \sigma^2 \right)^2 + 2\sigma^2(r - \mu_i)} \right) \cdot \sigma^{-2} < 0$$

$$\sigma^2 = \sigma_l^2 + \sigma_f^2 - 2\rho\sigma_l\sigma_f$$

$$\mu = \mu_f - \mu_l$$

The boundary condition implies that as R tends to zero the value of the option to implement the project should tend to zero as well. Therefore, since δ is negative, Z must be set equal to zero. The final solution is then

$$v = WR^\theta + \frac{R_a}{Lr}$$

If it is assumed that the investment is irreversible, then the value of land in forestry must equal its expected present value

$$V^f = \frac{R_{f,t}}{r - u_f} - \frac{L_t}{r - u_l} - \frac{K}{r}$$

or

$$\frac{V^f}{L} = \frac{R}{r - u_f} - \frac{1}{r - u_l} - \frac{K}{r} \cdot \frac{1}{L}$$

Given the value matching and smooth pasting conditions:

$$WR^\theta + \frac{R_a}{rL} = \frac{R}{r - u_f} - \frac{1}{r - u_l} - \frac{K}{r} \cdot \frac{1}{L} - \frac{C^f}{L}$$

$$\theta WR^{\theta-1} = \frac{1}{r - \mu_f}$$

the optimal switching rule is:

$$\bar{R}_F = R_f^* = (r - \mu_f) \frac{\theta}{\theta - 1} \left(\frac{L}{r - \mu_l} + \frac{K}{r} + C^f + \frac{R_a}{r} \right)$$

And the corresponding NPV rule would be

$$\text{NPV} \rightarrow \bar{R}_{F, \text{NPV}} = R_f^{*, \text{NPV}} (r - \mu_f) \left(\frac{L}{r - \mu_l} + \frac{K}{r} + C^f + \frac{R_a}{r} \right)$$

Note that Θ and β differ as the former depends on the volatility of the liability and its correlation to forestry revenues. As mentioned, this should lead to a higher level of uncertainty, the magnitude of this change being highly dependent on the correlation coefficient. The liability L , in addition to its impact on overall project uncertainty and the factor Θ , adds to the expected cost of the project.

3.2 Model 2: Stochastic Opportunity Cost and Reversibility

In the previous section uncertainty of forestry revenues (R_f) and liability (L) have been accounted for. However, anyone with experience in the agricultural sector knows the high volatility of agricultural revenues. Hence, most project owners will be uncertain about the future agricultural revenues and this should add to the uncertainty of the project. As a result, this should increase the real option optimal threshold value and reduce investment in the afforestation project.

As before, the model starts with an agricultural land owner who is assumed to maximize the value of their asset by solving:

$$V^{a,t}(R_{a,t}, R_{f,t}) = \max \left(R_{a,t} + \frac{V^{a,t+1}}{1+r}, R_{f,t} + \frac{V^{f,t+1}}{1+r} - C^f \right)$$

It is assumed that C is constant and that each R_i ($i=a,f$) follow a geometric Brownian motion with drift μ_i and volatility σ_i

$$dR_i = R_i \mu_i dt + R_i \sigma_i dz$$

$$dz = \varepsilon_i \sqrt{dt}$$

where ε_i are error terms distributed normally (0,1) and $E[\varepsilon_a \cdot \varepsilon_f] = \rho$

The optimal switching rule can be found by solving the problem using dynamic programming given the following Bellman equation

$$rV^a = E(R_a + dV^a)$$

Expanding by Ito's lemma

$$E(dV^a) = E[V_a^a dR_a + V_f^a dR_f + V_{af}^a dR_a dR_f + \frac{1}{2} V_{aa}^a dR_a^2 + \frac{1}{2} V_{ff}^a dR_f^2]$$

$$E(dV^a) = V_a^a R_a \mu_a dt + V_f^a R_f \mu_f dt + \rho \sigma_a \sigma_f R_a R_f V_{af}^a dt + \frac{1}{2} \sigma_a^2 R_a^2 V_{aa}^a dt + \frac{1}{2} \sigma_f^2 R_f^2 V_{ff}^a dt$$

and the Bellman equation can be written as

$$rV^a = R_a + V_a^a R_a \mu_a dt + V_f^a R_f \mu_f dt + \rho \sigma_a \sigma_f R_a R_f V_{af}^a dt + \frac{1}{2} \sigma_a^2 R_a^2 V_{aa}^a dt + \frac{1}{2} \sigma_f^2 R_f^2 V_{ff}^a dt$$

To make this partial differential equation more manageable, let $V^a(R_a, R_f) = R_a v(R_f/R_a)$

Then:

$$V_f^a = v'(R_f / R_a)$$

$$V_a^a = v - \frac{R_f}{R_a} v'(R_f / R_a)$$

$$V_{ff}^a = v''(R_f / R_a) \frac{1}{R_a}$$

$$V_{aa}^a = \left(\frac{R_f}{R_a} \right)^2 v''(R_f / R_a) \frac{1}{R_a}$$

$$V_{af}^a = -\frac{R_f}{R_a} v''(R_f / R_a) \frac{1}{R_a}$$

And

$$E(dV) = \left(v - \frac{R_f}{R_a} v' \right) R_a \mu_a dt + v' R_f \mu_f dt + \rho \sigma_a \sigma_f R_a R_f \left(-\frac{R_f}{R_a} \cdot \frac{1}{R_a} v'' \right) dt \\ + \frac{1}{2} \sigma_a^2 R_a^2 \left(\left(\frac{R_f}{R_a} \right)^2 \cdot \frac{1}{R_a} v'' \right) dt + \frac{1}{2} \sigma_f^2 R_f^2 \left(\frac{1}{R_a} v'' \right) dt$$

Finally, the Bellman equation can be written as

$$r R_a v = R_a + \left(v - \frac{R_f}{R_a} v' \right) R_a \mu_a dt + v' R_f \mu_f dt + \rho \sigma_a \sigma_f R_a R_f \left(-\frac{R_f}{R_a} \cdot \frac{1}{R_a} v'' \right) dt \\ + \frac{1}{2} \sigma_a^2 R_a^2 \left(\left(\frac{R_f}{R_a} \right)^2 \cdot \frac{1}{R_a} v'' \right) dt + \frac{1}{2} \sigma_f^2 R_f^2 \left(\frac{1}{R_a} v'' \right) dt$$

Dividing through by R_a and collecting like terms yields

$$rv = 1 + \left(v - \frac{R_f}{R_a} v' \right) \mu_a dt + \frac{R_f}{R_a} v' \mu_f dt - \rho \sigma_a \sigma_f \left(\frac{R_f}{R_a} \right)^2 v'' dt \\ + \frac{1}{2} \sigma_a^2 \left(\frac{R_f}{R_a} \right)^2 v'' dt + \frac{1}{2} \sigma_f^2 \left(\frac{R_f}{R_a} \right)^2 v'' dt$$

$$0 = 1 + v(\mu_a - r) + Rv'(\mu_f - \mu_a) + R^2 v'' \cdot \frac{1}{2} (\sigma_a^2 + \sigma_f^2 - 2\rho \sigma_a \sigma_f)$$

where the last line uses the substitution $R = R_f/R_a$. Thus, the simple differential equation above provides the following solution:

$$v_a = AR^\omega + BR^\pi + \frac{1}{r - \mu_a}$$

where N and M are constants to be determined later. $\omega (>1)$ and $\pi (<0)$ are the roots of the fundamental quadratic equation (Dixit and Pindyck 1994, p.142).

$$\sigma^2 = \sigma_a^2 + \sigma_f^2 - 2\rho \sigma_a \sigma_f$$

$$\mu = \mu_f - \mu_a$$

$$\omega = \left(\frac{1}{2}\sigma^2 - \mu + \sqrt{\left(\mu - \frac{1}{2}\sigma^2\right)^2 + 2\sigma^2(r - \mu_a)} \right) \cdot \sigma^{-2} > 1$$

$$\pi = \left(\frac{1}{2}\sigma^2 - \mu - \sqrt{\left(\mu - \frac{1}{2}\sigma^2\right)^2 + 2\sigma^2(r - \mu_a)} \right) \cdot \sigma^{-2} < 0$$

The boundary condition implies that as R tends to zero the value of the option to implement the project should tend to zero as well. Therefore, since π is negative, B must be set equal to zero. The final solution is then

$$v^a = AR^\omega + \frac{1}{r - \mu_a}$$

$$V^a = AR_f^\omega R_a^{1-\omega} + \frac{R_a}{r - \mu_a}$$

If it is assumed that investment is irreversible, then the value of land in forestry must equal its expected present value

$$V^f = \frac{R_{f,t}}{r - u_f} - \frac{K}{r}$$

or

$$v^f = \frac{V^f}{R_a} = \frac{R}{r - u_f} - \frac{K}{r} \cdot \frac{1}{R_a}$$

The optimal switching rule must satisfy the following conditions:

Value matching condition $v^a = v^f - \frac{C^f}{R_a}$

$$AR^\omega + \frac{1}{r - \mu_a} = \frac{R}{r - \mu_f} - \frac{K}{r} \cdot \frac{1}{R_a} - \frac{C^f}{R_a}$$

Smooth Pasting condition

$$v^a = v^f$$

$$A\omega R^{\omega-1} = \frac{1}{r - \mu_f}$$

Solving for the investment threshold provides:

$$\bar{R}_F = \left(\frac{R_f}{R_a} \right)^* = \frac{\omega}{\omega - 1} (r - \mu_f) \left(\frac{1}{r - \mu_a} + \frac{K}{r} \cdot \frac{1}{R_a} + \frac{C^f}{R_a} \right)$$

or the more intuitive representation

$$\frac{R_f}{(r - \mu_f)} = \frac{\omega}{\omega - 1} \left(\frac{R_a}{r - \mu_a} + \frac{K}{r} + C^f \right)$$

And the corresponding NPV rule would be

$$\text{NPV} \rightarrow \bar{R}_{F, \text{NPV}} = \left(\frac{R_f}{R_a} \right)^{*, \text{NPV}} = (r - \mu_f) \left(\frac{1}{r - \mu_a} + \frac{K}{r} \cdot \frac{1}{R_a} + \frac{C^f}{R_a} \right)$$

The factor ω is a function of σ_a and $\rho_{a,f}$. Given a low coefficient of correlation, the resulting volatility and investment threshold should be higher when compared to the model excluding agricultural revenue volatility.

Model 2a: Modeling the costly reversion of the project

The model developed above assumes that conversion is irreversible. In reality reversion may be possible but costly. Allowing for land use reversion would imply that the value of land in forestry would include the opportunity of reverting to agriculture at a later date. As a consequence, allowing for reversibility will increase the value of land in forestry due to greater managerial flexibility. This should in turn decrease the threshold value of $\bar{R}_F$ and favor investment in an afforestation project. This opportunity to reverse the investment decision can be valued in a similar way as the opportunity to start the project in the first place.

Let $V^f(\cdot)$ be the value of forest land which entitles the owner to a flow of profit R_f and at the same time, the opportunity to invest in agriculture. The agricultural project would yield revenues R_a per year, and would cost C^a to establish. The forest owner is assumed to maximize the value of their asset by solving:

$$V^{f,t}(R_{a,t}, R_{f,t}) = \max \left(R_{a,t} + \frac{V^{a,t+1}}{1+r} - C^a, R_{f,t} + \frac{V^{f,t+1}}{1+r} - K \right)$$

As before, it is assumed that C^a is constant and that each of R_i ($i=a, f$) follows a geometric Brownian motion with drift μ_i and volatility σ_i

$$\begin{aligned} dR_i &= R_i \mu_i dt + R_i \sigma_i dz \\ dz &= \varepsilon_i \sqrt{dt} \end{aligned}$$

where ε_i are error terms distributed normally (0,1) and $E[\varepsilon_a \cdot \varepsilon_f]^2 = \rho$

The Bellman equation for forestry now becomes

$$rV^f = E(R_f - K + dV^f)$$

Expanding by Ito's lemma

$$\begin{aligned} E(dV^f) &= E[V_a^f dR_a + V_f^f dR_f + V_{af}^f dR_a dR_f + \frac{1}{2} V_{aa}^f dR_a^2 + \frac{1}{2} V_{ff}^f dR_f^2] \\ E(dV^f) &= V_a^f R_a \mu_a dt + V_f^f R_f \mu_f dt + \rho \sigma_a \sigma_f R_a R_f V_{af}^f dt + \frac{1}{2} \sigma_a^2 R_a^2 V_{aa}^f dt + \frac{1}{2} \sigma_f^2 R_f^2 V_{ff}^f dt \end{aligned}$$

To make this partial differential equation more manageable, let $V(R_a, R_f) = R_f v(R_a/R_f)$

Then:

$$\begin{aligned} V_a^f &= v'(R_a / R_f) \\ V_f^f &= v - \frac{R_a}{R_f} v'(R_a / R_f) \\ V_{aa}^f &= v''(R_a / R_f) \frac{1}{R_f} \end{aligned}$$

$$V_{ff}^f = \left(\frac{R_a}{R_f} \right)^2 v''(R_a/R_f) \frac{1}{R_f}$$

$$V_{af}^f = -\frac{R_a}{R_f} v''(R_a/R_f) \frac{1}{R_f}$$

And

$$E(dV^f) = \left(v - \frac{R_a}{R_f} v' \right) R_f \mu_f dt + v' R_a \mu_a dt + \rho \sigma_a \sigma_f R_a R_f \left(-\frac{R_a}{R_f} \cdot \frac{1}{R_f} v'' \right) dt$$

$$+ \frac{1}{2} \sigma_f^2 R_f^2 \left(\left(\frac{R_a}{R_f} \right)^2 \cdot \frac{1}{R_f} v'' \right) dt + \frac{1}{2} \sigma_a^2 R_a^2 \left(\frac{1}{R_f} v'' \right) dt$$

The Bellman equation can be written as

$$r R_f v = R_f - K + \left(v - \frac{R_a}{R_f} v' \right) R_f \mu_f dt + v' R_a \mu_a dt + \rho \sigma_a \sigma_f R_a R_f \left(-\frac{R_a}{R_f} \cdot \frac{1}{R_f} v'' \right) dt$$

$$+ \frac{1}{2} \sigma_f^2 R_f^2 \left(\left(\frac{R_a}{R_f} \right)^2 \cdot \frac{1}{R_f} v'' \right) dt + \frac{1}{2} \sigma_a^2 R_a^2 \left(\frac{1}{R_f} v'' \right) dt$$

Dividing through by R_f and collecting like terms yields

$$rv = 1 - \frac{K}{R_f} + \left(v - \frac{R_a}{R_f} v' \right) \mu_f dt + \frac{R_a}{R_f} v' \mu_a dt - \rho \sigma_a \sigma_f \left(\frac{R_a}{R_f} \right)^2 v'' dt$$

$$+ \frac{1}{2} \sigma_f^2 \left(\frac{R_a}{R_f} \right)^2 v'' dt + \frac{1}{2} \sigma_a^2 \left(\frac{R_a}{R_f} \right)^2 v'' dt$$

$$0 = 1 - \frac{K}{r} + v(\mu_f - r) + R v'(\mu_a - \mu_f) + R^2 v'' \cdot \frac{1}{2} (\sigma_a^2 + \sigma_f^2 - 2\rho \sigma_a \sigma_f)$$

where the last line uses the substitution $R = R_a/R_f$. Thus, this simple differential equation can provide the following solution is

$$v_f = NR^\psi + MR^\gamma + \frac{R}{r - \mu_f} - \frac{K}{r}$$

where N and M are constants to be determined later. ψ (>1) and γ (<0) are the roots of the fundamental quadratic equation.

$$\psi = \left(\frac{1}{2}\sigma^2 - \mu + \sqrt{\left(\mu - \frac{1}{2}\sigma^2\right)^2 + 2\sigma^2(r - \mu_f)} \right) \cdot \sigma^{-2} > 1$$

$$\gamma = \left(\frac{1}{2}\sigma^2 - \mu - \sqrt{\left(\mu - \frac{1}{2}\sigma^2\right)^2 + 2\sigma^2(r - \mu_f)} \right) \cdot \sigma^{-2} < 0$$

$$\sigma^2 = \sigma_a^2 + \sigma_f^2 - 2\rho\sigma_a\sigma_f$$

$$\mu = \mu_a - \mu_f$$

The boundary condition implies that as R tends to zero the value of the option to implement the project should tend to zero as well. Therefore, since γ is negative, M must be set equal to zero. The final solution is then

$$v_f = NR^\psi + \frac{R}{r - \mu_f} - \frac{K}{r}$$

or

$$V^f = NR_f^{1-\psi} R_a^\psi + \frac{R_f}{r - \mu_f} - \frac{K}{r}$$

Assuming that once converted back the land has to stay in agriculture; agricultural land is worth the present value of its returns.

$$V^a = \frac{R_a}{(r - \mu_a)}$$

$$v^a = \frac{V^a}{R_a} = \frac{1}{(r - \mu_a)}$$

Using the value matching and smooth pasting conditions as before, R_a is equal to:

$$R_a = \frac{\psi}{\psi - 1} (r - \mu_a) \left(\frac{R_f}{r - \mu_f} - \frac{K}{r} + C^a \right)$$

and the corresponding NPV rule would be

$$\text{NPV} \rightarrow R_a = (r - \mu_a) \left(\frac{R_f}{r - \mu_f} - \frac{K}{r} + C^a \right)$$

In a world where conversion although costly is always possible, the value of land in each use is defined as follows:

$$V^f = NR_f^{1-\psi} R_a^\psi + \frac{R_f}{r - \mu_f} - \frac{K}{r}$$

$$V^a = AR_f^\omega R_a^{1-\omega} + \frac{R_a}{r - \mu_a}$$

To find the optimal conditions for conversion to forestry in terms of the

ratio $\bar{R}_F = \left(\frac{R_f}{R_a} \right)^*$, the following conditions must be met:

Value matching

$$-N\bar{R}_F^{1-\psi} - \frac{\bar{R}_F}{r - \mu_f} + A\bar{R}_F^\omega + \frac{1}{r - \mu_a} + \frac{K}{r} \cdot \frac{1}{R_a} + \frac{C^f}{R_a} = 0 \quad (3.4)$$

Smooth pasting

$$(\psi - 1)N\bar{R}_F^{-\psi} + \omega A\bar{R}_F^{\omega-1} - \frac{1}{r - \mu_f} = 0 \quad (3.5)$$

And the optimal conditions for conversion to agriculture, in terms of the

ratio $\bar{R}_A = \left(\frac{R_a}{R_f} \right)^*$ must meet the following conditions:

Value matching

$$-A\bar{R}_A^{1-\omega} - \frac{\bar{R}_A}{r - \mu_a} + N\bar{R}_A^\psi + \frac{1}{r - \mu_f} + \frac{K}{r} \cdot \frac{1}{R_f} + \frac{C^a}{R_f} = 0 \quad (3.6)$$

Smooth pasting

$$\psi N \bar{R}_A^{\psi-1} + (\omega - 1) A \bar{R}_A^{-\omega} - \frac{1}{r - \mu_a} = 0 \quad (3.7)$$

Given the parameters of the diffusion processes (μ_i and σ_i), the correlation coefficient ρ , the respective costs of conversion (C^a , C^f), and the discount rate r , the four equations (3.5-3.7) can be solve numerically to obtain the unknowns: $\bar{R}_A$, $\bar{R}_F$, N , and A .

Chapter 4 – Data and Estimation

This section presents the data set used and the results of the statistical analysis performed to estimate the parameter values of the models presented in the previous chapter. The parameters to be estimated include the discount rate (r), the cost of conversion between land use (C^f and C^a), the long term trend (μ_f , μ_a) and volatility (σ_f , σ_a) of agricultural and forestry revenues. In addition, the methodology used to estimate the carbon yield related to cultivation of hybrid poplar is also presented.

4.1 Discount rate (r)

The discount rate chosen should reflect the expected real market rate of return as it is intended to estimate the opportunity cost of capital tied up in the underlying asset. The actual residential mortgage lending rate for 5 years, reported by Statistics Canada (CANSIM II, table 1760043), is used as a proxy. This market rate was 5.6% as of March 2005 and averaged 5.83% over the previous 24 months. Given an expected inflation rate in the neighborhood of 2%, the Fischer equation would tell us that the real interest rate should be around 3.6% to 3.83%. Consequently, a discount rate of 4% will be used in conjunction with a sensitivity analysis.

4.2 Cost of Conversion to Forestry (C^f)

The cost of converting forage land into forestry is not negligible in the investment decision. This cost includes land preparation, planting stocks, and weed/pest control during the first years of establishment. The cost may vary depending on the intensity of management but most estimates range between \$1250/ha and \$2000/ha. The conversion

cost to be used in this study must reflect the sunk cost related to a commitment in growing hybrid poplars. Cost related to site preparation, planting, weed/pest control, taxes, insurance and depreciation are considered as sunk. Conversely, land and/or machinery investment included in the various budgets are not regarded as sunk. Estimates used in previous studies are presented in table 4.1. A cost of \$1500/ha is used for the present study.

Table 4.1:

Hybrid Poplar Establishment Cost

	<u>Cost Estimates/ha</u>
Kiecker and Schoessow (2000)	\$1367
Van Kooten et al. (1999)	\$1270
McKenney et al. (2004)	\$1400 to \$2600
Van Kooten, Shaikh, and Suchanek (2002)	\$1500 to \$2000
Van Kooten (2000)	\$1200 to \$4000

4.3 Cost of Conversion to Agriculture (C^a)

The cost of converting forested land into forage land must include the cost of removing stumps and preparing land for an agricultural crop. Estimates for those costs are hard to obtain, yet Quebec agricultural appraisers have suggested a cost of \$3000 to \$4000 per hectare. These values come from experience of deforestation activities brought by crop land requirements related to hog production in the province of Quebec. To the author's knowledge there do not exist data for such deforestation activities in Western Canada.

It should also be noted that these estimates come from deforestation of land that may have never been deforested before and that may have been covered by mature hard wood species such as maple or oak. Given that hybrid poplars are expected to be harvested after 12 years, a relatively young age, the lowest estimate of \$3000/ha will be used.

4.4 Agricultural Revenues (R_a)

To estimate the diffusion parameters (μ and σ) related to forage crop net revenues on the Canadian Prairies, the data set must provide information about the variability and the long term trend of net revenues. Time series of Saskatchewan tame hay yield and prices were obtained from the Saskatchewan Agriculture, Food, and Rural Revitalization (SAFRR, 2003a). The data set contained provincial yearly data for the period of 1971 to 2002, thus thirty two observations were available. This sample size is thought to be optimal as yield can only be measured on a yearly basis and price data were limited to the post 1971 period. This last point is justified by the structural changes that the agricultural industry experienced during the 60's and 70's. The increasing trade volume affected price behavior, and production patterns were altered by the advent of the green revolution. Thus, only post 1971 data were kept even though the number of observations is small. Also, crop insurance offering protection at 50, 60 and 70% of long term average yield is available in Saskatchewan for tame hay producers. The loss in production is covered at the average price of the last 5 years. In accordance with the program rules at the 60% level of coverage, the revenues for 1980, 95, 97 and 2002 are corrected for loss in production (Saskatchewan Crop Insurance 2005).

The yield and price data are presented in figure 4.1 and 4.2 respectively and total revenues (price · yield) are presented in figure 4.3. The Farm input price index for crop production in western Canada (CANSIM II, tables 3280014 & 3280001) is used in conjunction with the production costs provided by SAFRR (2003b) to obtain a time series of tame hay net revenues per hectare. Finally, the consumer price index (including all goods) published by Statistics Canada (CANSIM II, table 3260002) was used to find the net real revenues per hectare as shown in figure 4.4.

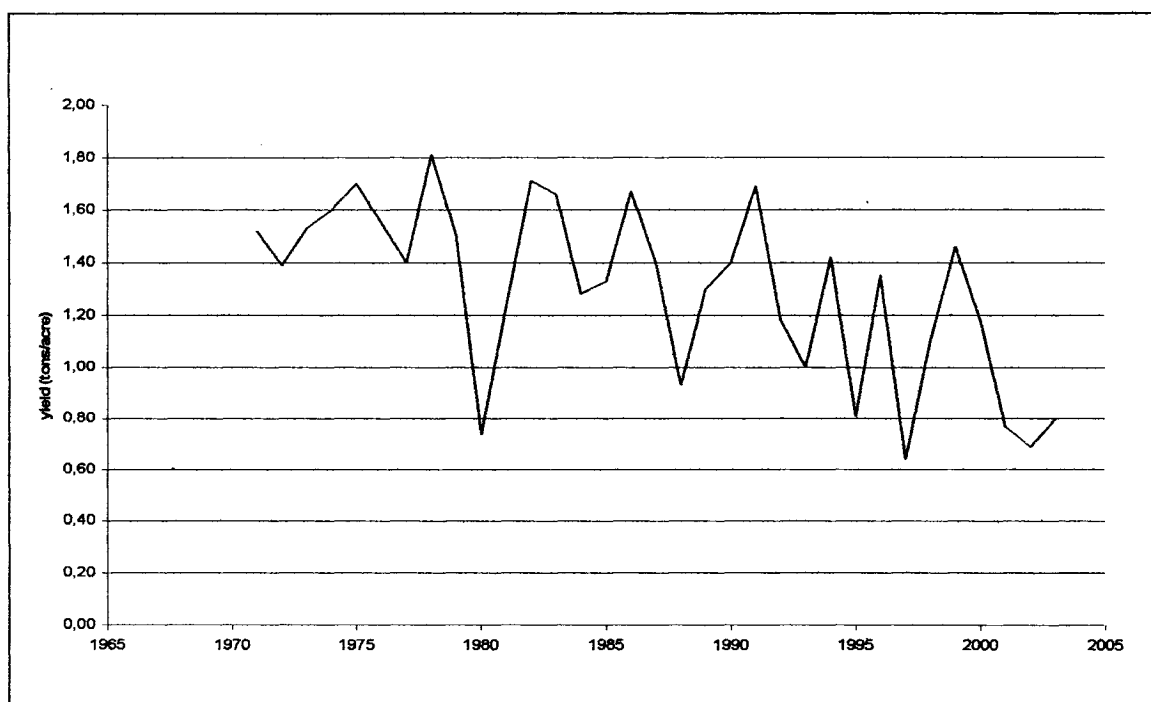


Figure 4.1: Saskatchewan tame hay yield in tons per acre (1971-2002)
Source: SAFRR 2003a

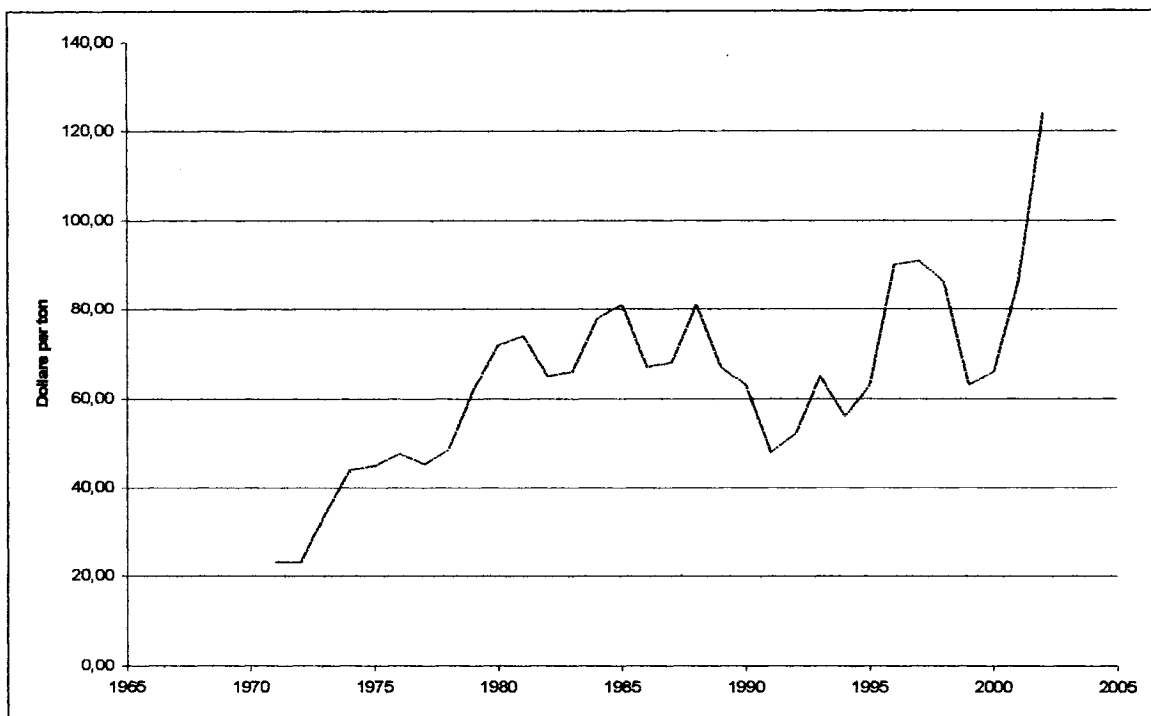


Figure 4.2: Saskatchewan tame hay price in Canadian nominal dollars per ton (1971-2002).
Source: SAFRR 2003a

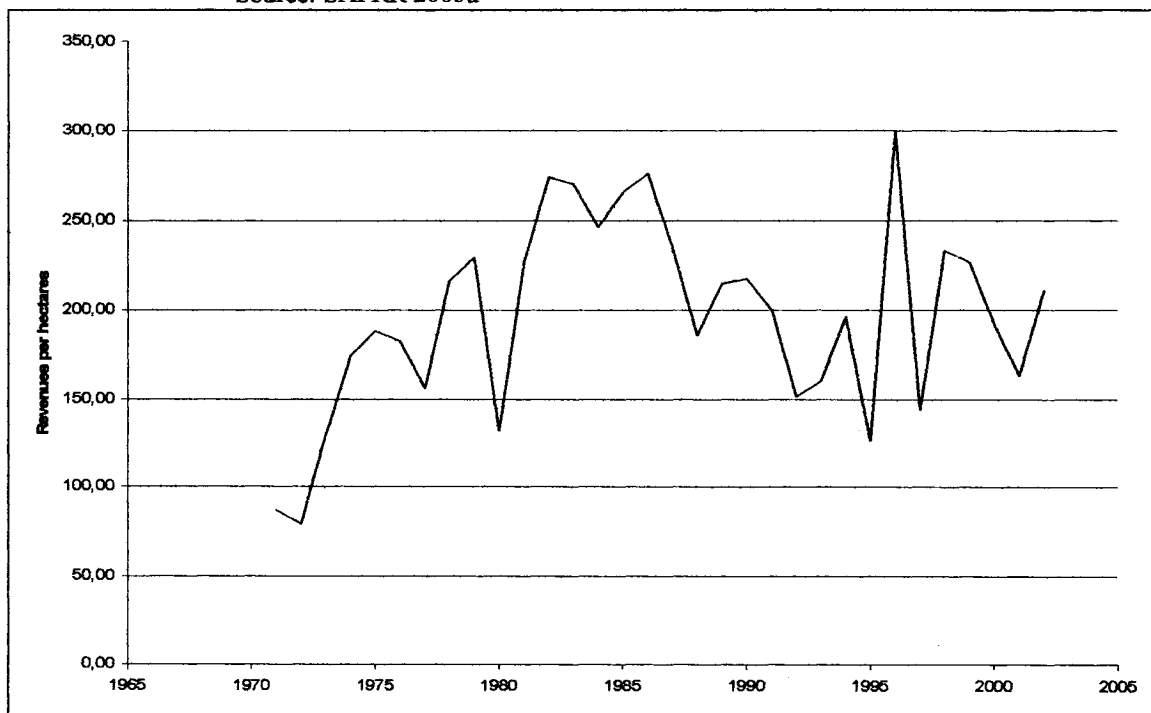


Figure 4.3: Saskatchewan tame hay nominal revenues in Canadian dollars per ton (1971-2002)

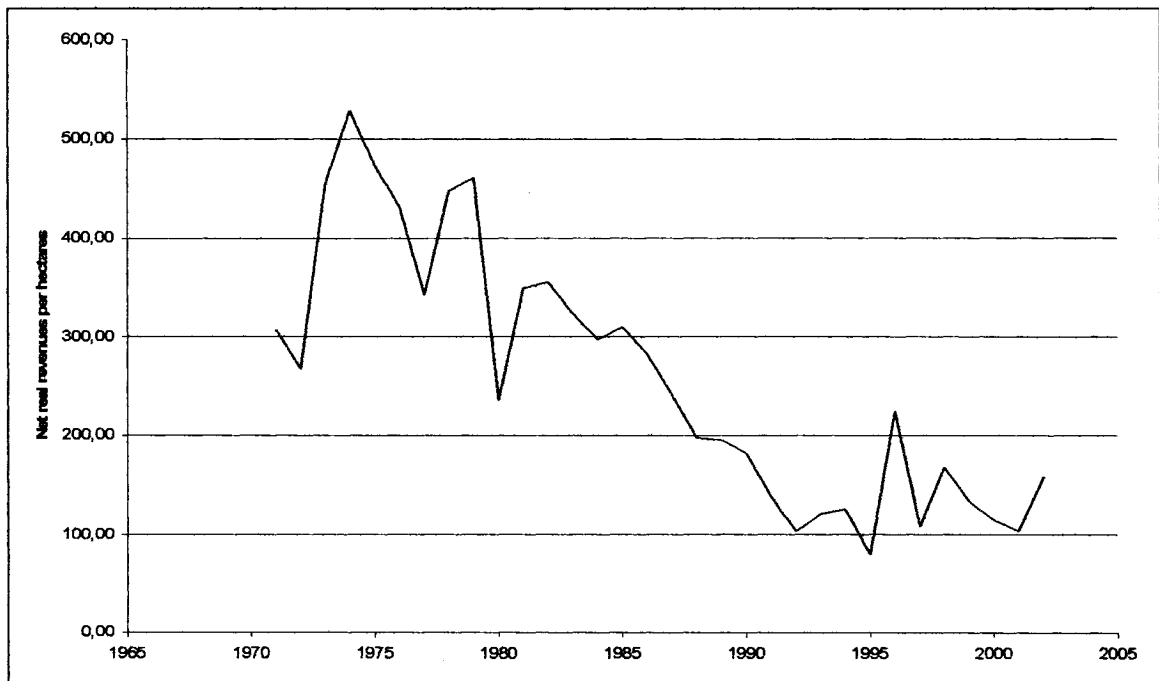


Figure 4.4: Saskatchewan tame hay net real revenues per hectare in Canadian dollars per ton (1971-2002)

The series of real net revenues was used to estimate the parameters of the geometric Brownian motion by applying the methodology shown in appendix 1. The estimate of the drift (μ_a) is found to be statistically insignificant, and a value of zero will be used in the study. This implies that, in the long run, it is expected that forage cropping revenues will grow at the inflation rate.

The estimated standard deviations (σ_a) of real tame hay price, real tame hay gross revenues and real tame hay net revenues are respectively of 0.196, 0.284, and 0.301. According to Pindyck (1991), "...in volatile markets, the standard deviation of annual changes in a project's value can easily exceed 20 or 30 percent" (p.1123). Table 4.2 presents some values of the volatility parameters found in the agricultural literature.

Table 4.2 Volatility Estimates

	<u>Project</u>	<u>Standard deviation(σ)</u>
Price and Wetzstein 1999	Peach orchard investment	0.25
Pagano 1993	Adoption of free stall dairy housing	0.21
Khanna et al. 2000	Site specific crop management	0.225
Carey and Zilberman 2002	Irrigation technology investment	0.15
Diederer, et al. 2003b	Energy-saving technology adoption in Dutch greenhouses	0.16

Volatility estimates from the Saskatchewan data set may seem to be high at first sight. However, the projects considered in the reported studies present some dissimilarities with the agricultural revenues considered here. For example, Diederer et al. (2003b) analyzed the investment in energy saving technologies for Dutch greenhouses and considered only the uncertainty related to the energy (gas) price. Similarly, Carey and Zilberman (2002) only included the uncertainty associated with the market price of water while Khanna et al. (2000) looked at the uncertainty linked to corn price and Pagano (1993) included the uncertainty stemming from milk production and feed cost.

All of these examples illustrate the importance of the potential project's nature when determining the uncertainty related to it. In each case the revenues and costs of the implemented project are assumed to differ only slightly from the original situation, thus yielding a relatively small investment return volatility. For example in Carey and Zilberman (2002) only the water requirements change under the implemented project hence the volatility of variables other than water are not considered. In the present case, the volatility of price, yield, and cost have to be considered. Finally, Price and Wetzstein

(1999) are the only ones that considered both price and yield uncertainty, which explain their higher volatility estimate.

The model developed in chapter 3 assumes that net revenues to agriculture follow a non-stationary diffusion process. Yet, the stationarity of the true process is debatable. Economic theory would suggest that the supply response should prevent the price from wandering too far from the long run equilibrium. Hence, price should be bounded above, which is not the case for geometric Brownian motion.

The stationarity of a given process can be studied statistically by performing a Dickey-Fuller test. In order to carry out such a test, the number of autoregressive lags to be considered in the regression must be determined. Including too many lags in the regression would reduce the power of the test and on the other hand too few lags would not adequately capture the properties of the process (Enders 1995). One way to determine the correct number of lags is to look at the partial autocorrelation function (PACF) which presents the marginal explanatory power of the different lags.

“...it [PACF] measures the additional correlation between x_t and x_{t-k} after adjustments have been made for the intermediate variables $x_{t-1}, \dots, x_{t-k+1}$ ”
Mills 1990, p.78

The PACF of agricultural net real revenues (see figure 4.5) is indicative of an autoregressive process of order 1 (AR(1)) since only the first lag has a significant partial correlation at the 5% level of significance. Other methods are also available to determine the adequate lag order. They take the form of criteria that impute a penalty to over-parameterization of the autoregression. As a result, adding a lag to the regression will

increase the explanatory power (reduction in residual sum of squares) but will also increase the penalty function included in those criteria. The selection criteria reported in Table 4.3 suggests an AR(2) as the best representation of the series.

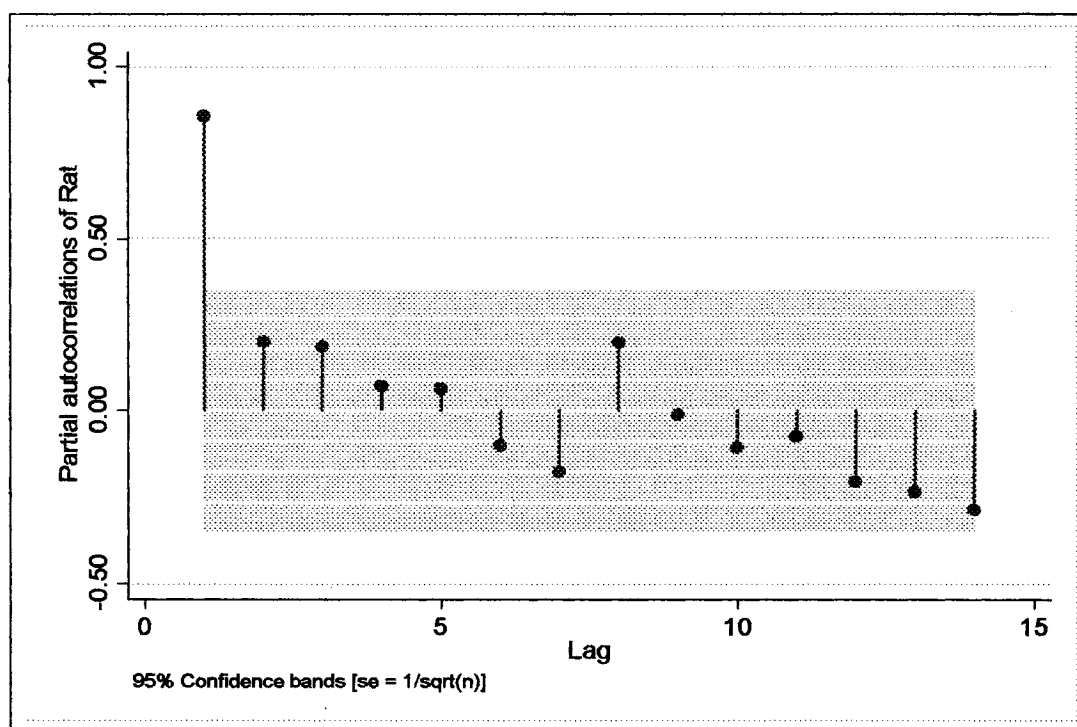


Figure 4.5: Partial autocorrelation function of annual agricultural net real revenues ($R_{a,t}$)

Table 4.3

Selection order criteria

Constant included in models

Sample: Obs = 28

Lag	df	p	AIC	SBIC
0	-	-	12.2884	12.3359
1	1	0.000	10.8718	10.967
2	1	0.038	10.79*	10.9328*
3	1	0.217	10.8069	10.9972
4	1	0.631	10.8701	11.108

AIC= Akaike Information Criterion, BIC= Schwarz Bayesian Information Criterion

In order to determine the best specification to use between an AR(1) or an AR(2), a Ljung-Box Q-statistic, designed to detect serial correlation, is performed on the residuals of the AR(1) model. Results, which are reported in Table 4.4, fail to reject the white noise hypothesis for the residuals of the AR(1) process, $R_{a,t} = \alpha_0 + \alpha_1 R_{a,t-1} + \varepsilon_t$. In addition the ACF and PACF of the residuals (figure 4.6 and 4.7) conform to the white noise hypothesis. Hence the residuals from the AR(1) model cannot be differentiated from a white noise process, and consequently this representation is used to test for stationarity of the time series.

Table 4.4

Ljung-Box Q-statistic for the residual of the AR(1) model of the agricultural revenues:

Portmanteau test for white noise

Portmanteau (Q) statistic = 4.6438

Prob > chi2(13) = 0.9822

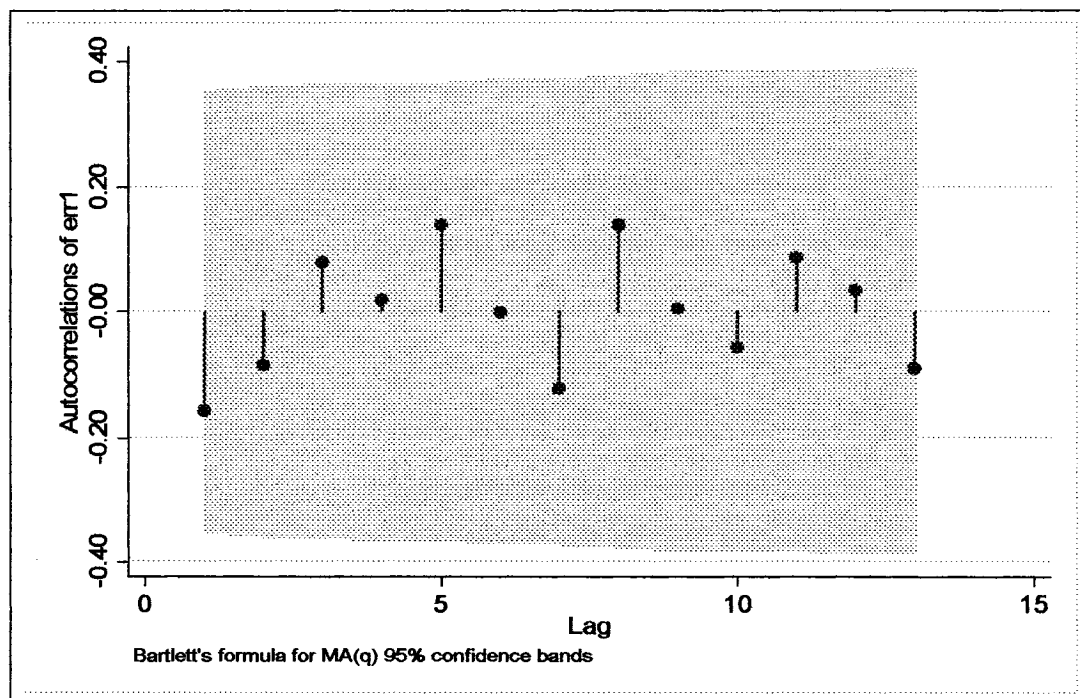


Figure 4.6: Autocorrelation function of the residuals from regression $R_{a,t} = \alpha_0 + \alpha_1 R_{a,t-1}$

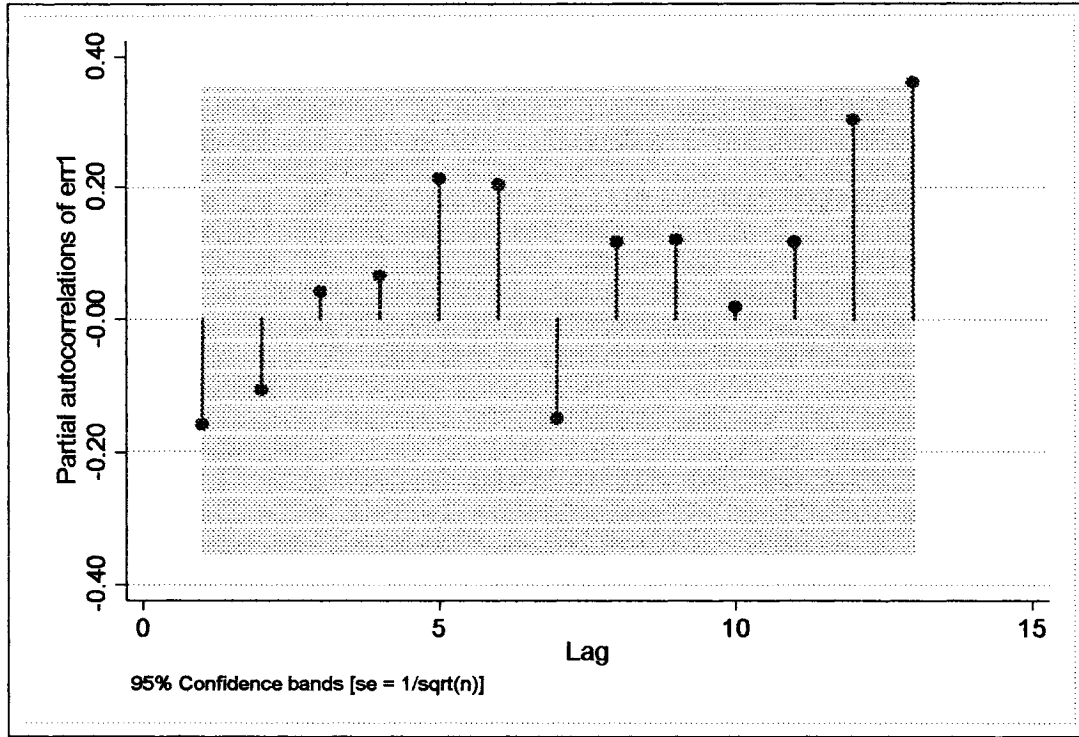


Figure 4.7: Partial autocorrelation function of the residuals from regression $R_{a,t} = \alpha_0 + \alpha_1 R_{a,t-1}$

To test for the presence of a unit root a variant of the Dickey-Fuller test, the DF-GLS (Dickey-Fuller Generalized Least Square) test is performed (Elliot et al. 1996). The first step of the DF-GLS test is to estimate the deterministic components (β_0 and β_1) by a GLS regression ($R_{a,t} = \hat{\beta}_0 + \hat{\beta}_1 t + error$) where the error term is assumed to be AR(1) with the autoregressive coefficient equal to $1 - \frac{13.5}{T}$ ¹³. Then an Augmented Dickey-Fuller (ADF)

test ($\Delta R_{a,t}^r = \rho R_{a,t-1}^r + \sum_{i=1}^p \beta_{i+1} \Delta R_{a,t-i}^r$) is performed on the detrended series ($R_{a,t}^r = R_{a,t} - \hat{\beta}_0 - \hat{\beta}_1 t$). This test is said to have greater power than the original Dickey-

¹³ This specification was suggested by Elliot et al. 1996 to obtain a more powerful test given a certain sample size.

Fuller test performed on OLS detrended series since OLS estimation of deterministic parameters is inappropriate when the root is close to unity (Elliot et al. 1996; Ng and Perron 2001).

The result of the DF-GLS test using the AR(1) representation are reported in Table 4.5. Results suggest a rejection of the hypothesis of a unit root and non-stationarity of the time series at the 10% level of significance. However, when performing the same test using the AR(2) representation (also reported in Table 4.5) the test fails to reject the null hypothesis of non-stationarity. In addition the modified AIC criterion (MAIC as proposed by Ng and Perron 2001) reported by the DF-GLS results would support the use of an AR(2) for the test. Given the recognized lack of power of the Dickey-Fuller test and considering the theoretical arguments, one can conclude in favor of a stationary process, yet the diagnosis remains ambiguous.

Table 4.5
DF-GLS for Agricultural net real revenues

Maxlag(1) Number of obs = 30

Lags	DF-GLS tau test statistic	1% Critical Value	5% Critical Value	10% Critical Value
1	-3.088	-3.770	-3.190	-2.890

Maxlag(2) Number of obs = 29

Lags	DF-GLS tau test statistic	1% Critical Value	5% Critical Value	10% Critical Value
1	-1.943	-3.770	-3.190	-2.890
2	-2.421	-3.770	-3.190	-2.890

Min SC = 8.051161 at lag 1 with RMSE 49.87235

Min MAIC = 8.453743 at lag 2 with RMSE 49.598875

4.5 Forestry Revenues (R_f)

As with agricultural revenues, a time series of forestry revenues is needed to provide information about the long term trend and the variability of returns. Revenues to forestry are made up of timber sales and carbon storage services. It is assumed that timber is sold mainly for pulp and paper purposes (75%) and to a lesser extent for lumber use (25%).

A time series of revenues is constructed from price indexes of pulpwood chips and softwood lumber for the region of the British Columbia Interior¹⁴ as provided by Statistics Canada (CANSIM II, tables V1575027 & V1575069). The December 2004 market prices were \$35.23/m³ and \$45.57/m³ for deciduous pulpwood in the interior of B.C. and sawlogs respectively, providing a blended price of \$37.82/m³ (British Columbia Ministry of Forestry, 2004). In comparison, cottonwood (a type of poplar) was selling for \$36.38/m³ in B.C. Coastal markets (British Columbia Ministry of Forestry, 2004) and a publication of Alberta Agriculture Food and Rural Development (AAFRD, 2003) reports average prices of \$29/m³ for deciduous wood sold in Alberta over the 1997-2002 period. Based on the foregoing, a value of \$37/m³ is used for the study and the gross timber sales revenues per cubic meter in nominal and real terms are shown in figures 4.8 and 4.9 respectively.

¹⁴ Time series for hardwood lumber were unavailable for Western Canada. They were also unavailable for a pulpwood series for the Prairie Region.

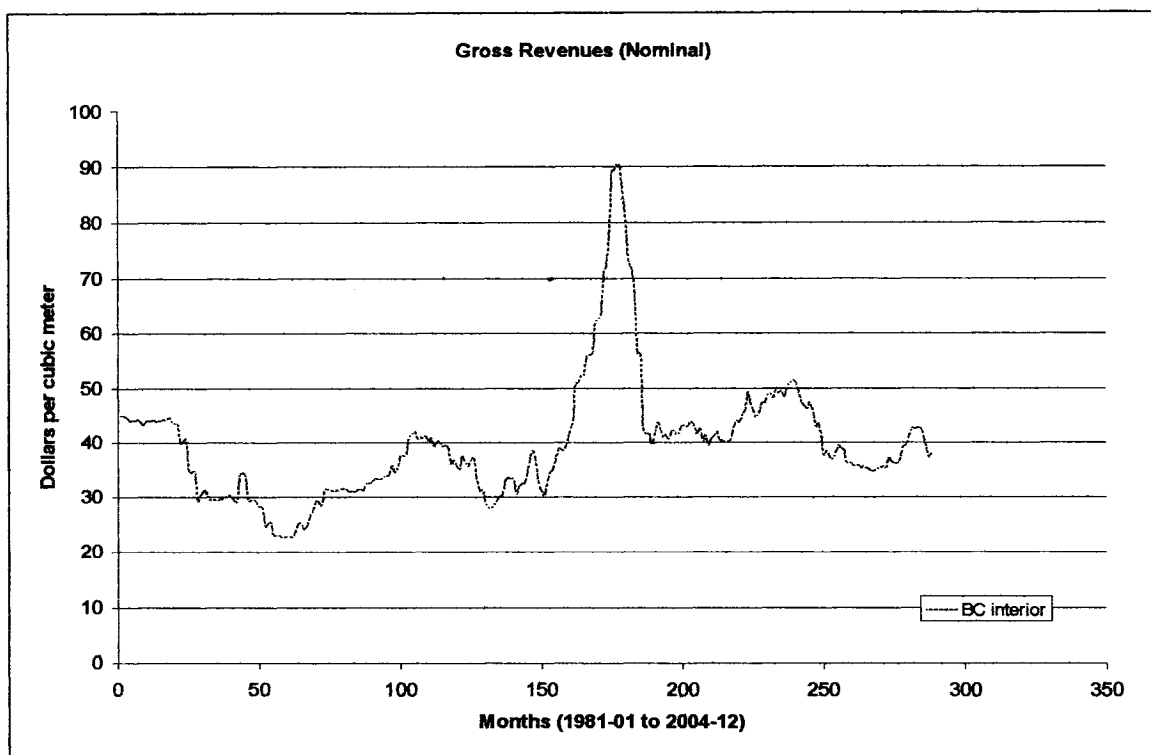


Figure 4.8: Gross nominal timber sale revenues per cubic meter

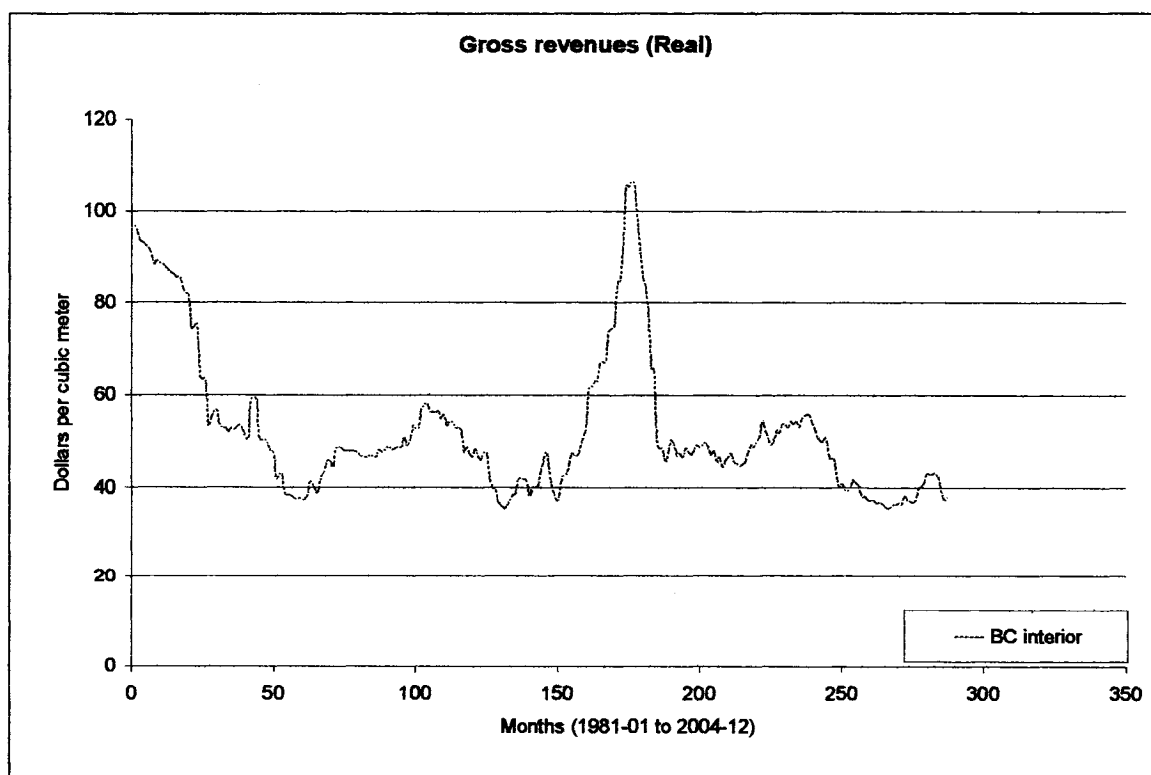


Figure 4.9: Gross real timber sale revenues per cubic meter

From gross revenues, harvesting and hauling costs have to be subtracted. Van Kooten et al. (1999) used harvest plus hauling costs varying between \$18/m³ and \$26/m³, AAFRD (2003) reports logging costs and hauling costs of \$12/m³ and \$14/m³ respectively, while the Saskatchewan Forest Center (2003) reports harvesting costs of \$15/m³. This study uses a harvesting plus hauling cost of \$25/m³ leading to a stumpage value¹⁵ of \$12/m³. This figure is compared with other values found in the literature; McKenney et al. (2004) used a mean stumpage value of \$12/m³, Van Kooten et al. (2000) used \$3/m³ while Van Kooten et al. (2002) assumed a value of \$25/m³.

The time series of net real revenues to timber sales are shown in Figure 4.10. The estimated diffusion parameters are -0.05 for the drift (μ_f) and 0.26 for the standard deviation (σ_f). However, most of the decline in net revenues comes over the first 40 periods (1981 to 1984). When estimating the parameters with truncated data from June 1984 to December 2004, the parameter estimates are -0.01 for the drift (μ_f) and 0.27 for the standard deviation (σ_f) but the drift estimate is found to be statistically insignificant (see appendix 1).

In addition, the AAFRD (2003) reports optimistic market conditions for private woodland owners due to an increasing North American and World demand for timber, limited supply expansion on public land, and the development of new markets for deciduous species. In light of this information the estimates obtained from the truncated data set are

¹⁵ Stumpage value is the value of trees as they stand in the forest. Stumpage value=wood value at mill-hauling and harvesting costs, \$37-\$25=\$12/m³

thought to be a better proxy for expected future returns and are therefore used in this study.

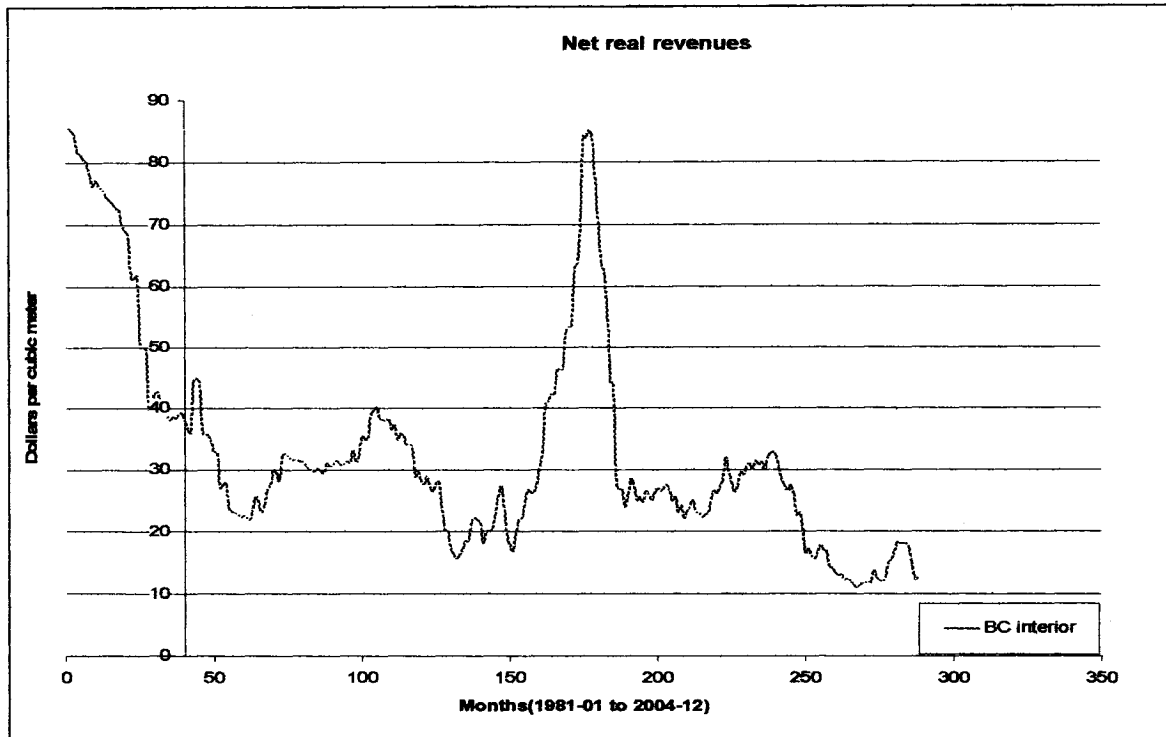


Figure 4.10: Net real timber sale revenues per cubic meter. Truncation at $t=40$.

The stationarity of this series is also investigated through a DF-GLS procedure. First the PACF (Figure 4.11) suggests an AR(4) as being the optimal representation. The information criteria reported in Table 4.6 confirms this result. As well, the residuals of the regression $R_{a,t} = \alpha_0 + \alpha_1 R_{f,t-1} + \alpha_2 R_{f,t-2} + \alpha_3 R_{f,t-3} + \alpha_4 R_{f,t-4}$ are tested for serial correlation with a Ljung-Box Q-test and the results (see Table 4.7) fail to reject the white noise hypothesis. Finally the ACF and PACF of the residual (figure 4.12 and 4.13) also support the white noise hypothesis and as a consequence the AR(4) specification is used to perform the unit root test.

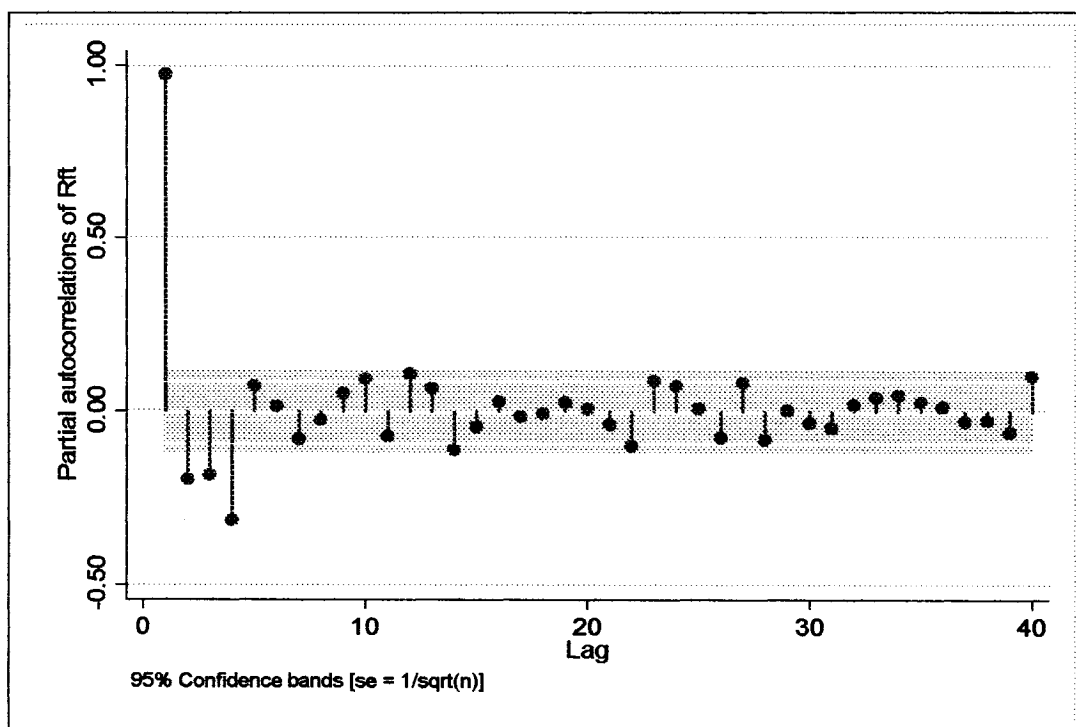


Figure 4.11: Partial autocorrelation function of forestry net real revenues (R_{ft})

Table 4.6

Selection order criteria

Constant included in models

Sample: Obs = 284

Lag	df	P	AIC	SBIC
0	-	-	8.48747	8.50031
1	1	0.000	4.79256	4.81826
2	1	0.000	4.76025	4.7988
3	1	0.000	4.73267	4.78406
4	1	0.000	4.63557*	4.69982*
5	1	0.000	4.6931	4.77039

Table 4.7

Ljung-Box Q-statistic for the residual of the AR(4) model of the timber revenues:

Portmanteau test for white noise

Portmanteau (Q) statistic = 35.1370

Prob > chi2(40) = 0.6887

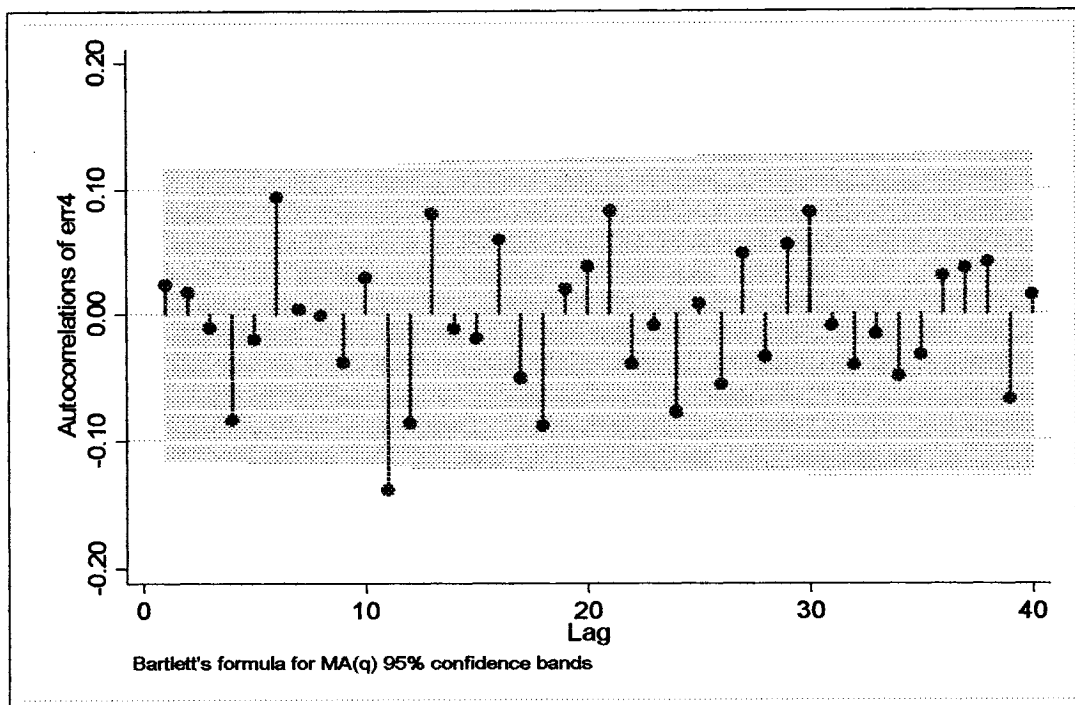


Figure 4.12: Autocorrelation function of the residuals from regression $R_{e,t} = \alpha_0 + \alpha_1 R_{e,t-1} + \alpha_2 R_{e,t-2} + \alpha_3 R_{e,t-3} + \alpha_4 R_{e,t-4}$

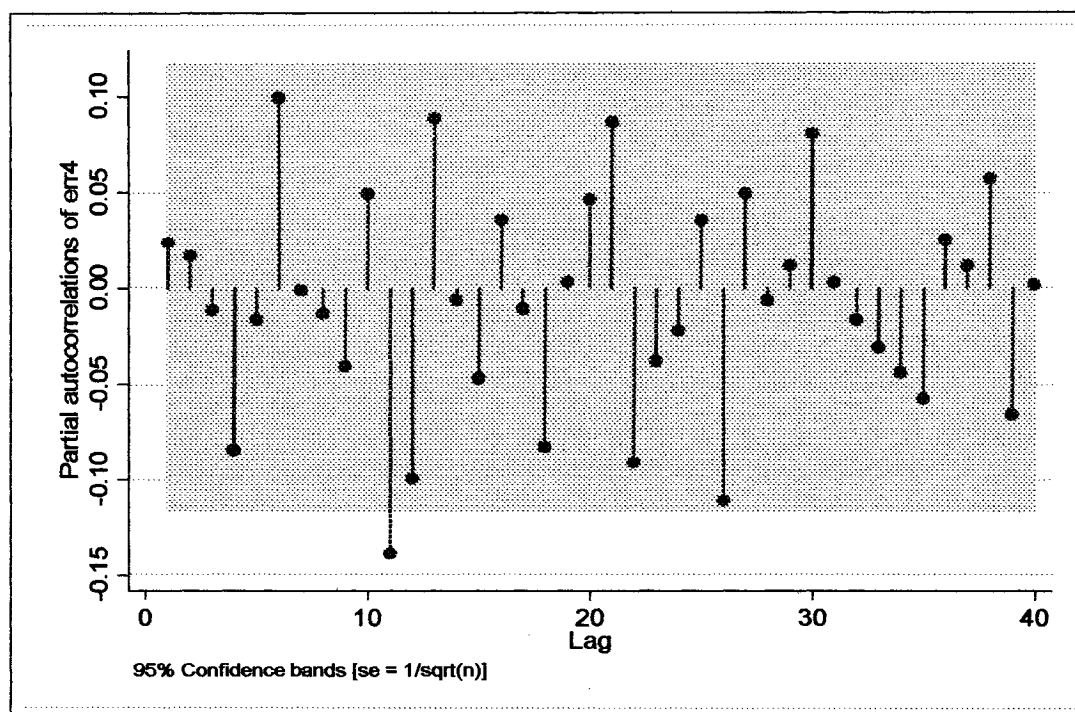


Figure 4.13: Partial autocorrelation function of the residuals from regression $R_{e,t} = \alpha_0 + \alpha_1 R_{e,t-1} + \alpha_2 R_{e,t-2} + \alpha_3 R_{e,t-3} + \alpha_4 R_{e,t-4}$

The results of the DF-GLS regression are reported in Table 4.8. The test fails to reject the hypothesis of non-stationarity. In addition the MAIC criterion, reported with the result, support the use of an AR(4) representation. Yet, the SC criterion would suggest the use of an AR(3). To clarify the situation a Ljung-Box Q-test was performed on the residuals of the AR(3) regression and revealed the presence of serial correlation (see Table 4.9). As a consequence the AR(3) representation is discarded and it is assumed that net real revenues to timber sales follow a non-stationary process.

Additionally to the revenues related to the sale of timber, the income from carbon storage services must be included. As of May 2005, no time series of carbon prices were available. Instead, the carbon price is assumed to behave in a similar fashion to the SO₂ allowance market value (see figure 4.14). Christoffersen (2003) reports a yearly standard

Table 4.8

DF-GLS for Timber net real revenues Maxlag(4) Number of obs = 283				
lags	DF-GLS tau Test Statistic	1% Critical Value	5% Critical Value	10% Critical Value
1	-1.260	-3.480	-2.890	-2.570
2	-1.529	-3.480	-2.890	-2.570
3	-2.132	-3.480	-2.890	-2.570
4	-1.948	-3.480	-2.890	-2.570
Min SC = 1.865276 at lag 3 with RMSE 2.441813				
Min MAIC = 1.836198 at lag 4 with RMSE 2.434616				

Table 4.9

Ljung-Box Q-statistic for the residual of the AR(3) model of the timber revenues:

Portmanteau test for white noise

Portmanteau (Q) statistic = 76.4447
Prob > chi2(40) = 0.0005

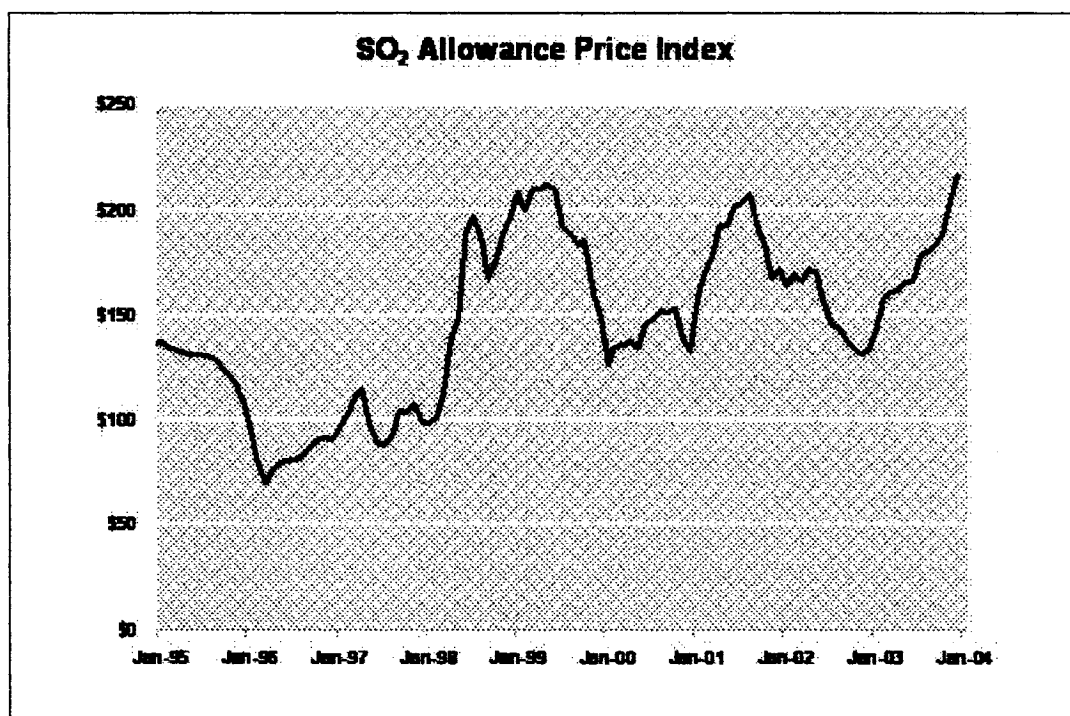


Figure 4.14: Source: U.S. Environmental Protection Agency

deviation of $\sigma=0.25$ for the SO₂ allowance market between 1994 and 2003 and also reports a drift rate close to zero. In the case of carbon credits there is little knowledge of whether the price will be trending upward or downward. On the one hand, there could be a technological breakthrough that would reduce emissions and lessen the demand for carbon credits. On the other hand, climate change damages could be underestimated and/or economic development may be greater than anticipated and the need for further emission reductions may become pressing in such a way that the carbon credit price will increase. Not knowing which of the two alternatives is most likely; a drift rate of zero was used thus reflecting ignorance about the future carbon price.

Simulating forestry and carbon revenues

Given that net revenues to the afforestation project must follow a unique geometric Brownian motion, Monte Carlo simulation is used to estimate the parameters of the total forestry revenue diffusion process. It is important to note that the revenues to forestry are treated as a yearly rent or annuity which could be associated with an incremental contract in which landowners receive an annual payment equivalent to the growth of the forest on their land (AAFRD, 2003). Project revenues are made up of carbon and timber revenues:

$$\text{Timber Revenues: } R^T = \sum_{i=1}^2 V(iT) \cdot P_{iT}^T \cdot e^{-rT}$$

$$\text{Carbon Revenues: } R^C = \sum_{t=1}^T S(t) \cdot P_t^C \cdot e^{-rt} - \sum_{i=1}^2 L_{iT} \cdot e^{-rT}$$

Where L_T is the liability cost related to the use of Offset Credits (OCs) and P^C is the value of carbon adjusted for TCs or OCs depending on which is used. $S(t)$ is the amount of carbon stored at time t and $V(T)$ is the volume of marketable timber at the time of harvest T and P_{iT}^T is the stumpage price at time of harvest. Finally $i=1,2$ represents the number of rotations and the time horizon considered to evaluate the impact of carbon sequestration on project revenues which is two complete rotations or 24 years for the present study.

The parameters needed are the expected drift rate or growth rate and the volatility of the net forestry revenues over time. Since the drift parameter of carbon and timber are assumed to be zero then the total forestry revenues should also have a zero drift. To obtain the variance, since revenues to forestry accrue unevenly over time, the total revenues were considered over a horizon of 24 years (2 rotations in length). First the total net project revenues over the 24 year period are computed given the expected prices

(using the assumed price at time 0 and the drift parameters). This provides a measure of expected revenues which can be compared to the simulated revenues and from there the variance of the total project revenues can be computed following the methodology presented in appendix 2.

4.6 Carbon Yields

The amount of carbon sequestered is divided amongst various pools as presented in table 4.10. The first pool is stem wood, measured in m³/ha, which is determined by the following Chapman-Richards function:

$$V(t) = A(1 - e^{-kt})^m$$

Table 4.10
Carbon Pools in tC/ha

Year	Above Ground C	Roots C	Soil C	Litter C	Total C
5	15.3	4.65	4.8	1.3	26.09
12	58.5	10.94	11.5	3.1	84.10

The parameters of hybrid poplar's growth function in a boreal region are A=329, k=0.156, and m=3 (Guy and Benowicz 1998). The above ground biomass includes leaves, branches, and stems and amounts to 1.57·V(t). At 12 years of age, the stem biomass is 199m³/ha which is consistent with numbers of 100 to 200 m³/ha used by the Saskatchewan Forest Center (2003), and with yields of 12 to 20m³/ha used by McKenney et al. (2004). Carbon content is assumed to be 0.187 metric tonnes/m³ (Van Kooten et al. 2000).

Biomass contained in roots is obtained, in metric tonnes per hectares, from the following formula (Van Kooten et al. 1999):

$$R = 1.4319 \cdot [G(t)]^{0.639} \quad 4.1$$

Where $G(\cdot)$ is the above ground biomass measured in metric tonnes/ha, the biomass conversion factor used is 0.9 metric tonnes/m³ (AAFRD, 2003). At a stand age of 12 years, equation 4.1 provides a ratio of roots to stem biomass of 29%, which is in line with the mean value of 27% reported by Cairns et al. (1997) for boreal regions. Root carbon is modeled as a one-time growth, and following the first rotation the sink is assumed to be permanently filled. This is justified as the decomposition of former stand roots shall offset the gain of the roots of the new stand thus bringing equilibrium. Carbon contained in the litter pool is assumed to grow at a rate of 0.26tC/yr for 50 years (Van Kooten et al. 1999). This linear approximation is close to other estimates provided by Smith and Heath (2002) and is conservative compared to the default values proposed by the IPCC (2003) for Boreal and Cold Temperate regions.

The last pool to be considered is soil carbon. It is assumed that 0.96 tons C/ha accumulates in this pool on a yearly basis for the first 50 years (Van Kooten et al. 1999, McKenney et al. 2004). Upon harvest, it is assumed that all of the carbon contained in above ground biomass is released. Only soil, litter, and root carbon are not affected by harvest however reversion to agriculture would empty all of these pools. The carbon yield curves under permanent sequestration and periodic harvest are depicted in figure 4.15.

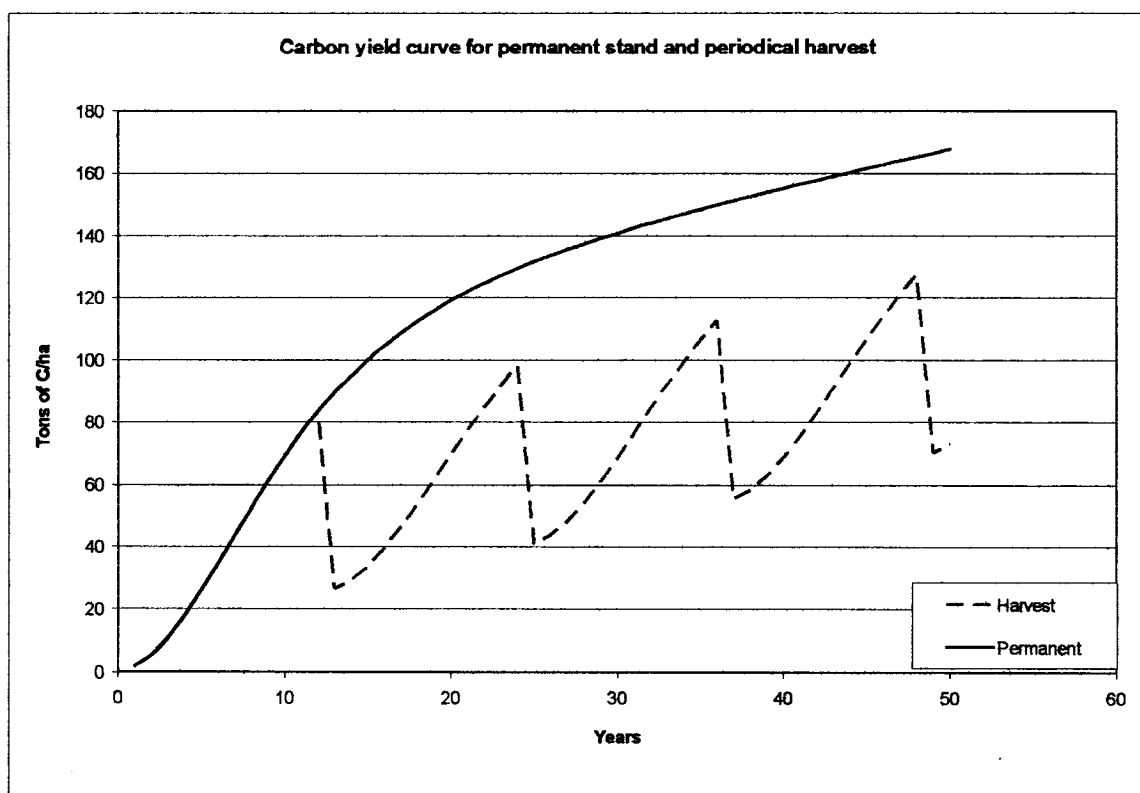


Figure 4.15: Carbon yield curves in tons of C per hectare

Chapter 5: Results and Discussion

The intent of the present study is to explore a carbon market's impact on incentives to create carbon sinks through afforestation of marginal agricultural land. In chapter two, the cost engineering or budgeting approach was argued to be deficient, in particular because of the omission of uncertainty related to the decision, which may create friction in BMPs adoption. Nevertheless, section 5.1 will present scenarios built using the NPV methodology that will serve for comparison purposes since previous studies are for the most part based on this approach. Comparing budgeting results with the real option approach will allow us to distinguish between the non-permanence impact and the real option effect on the investment incentives. This is followed by a presentation and analysis of results from a basic real option model (Model 1 and 1a) which includes forestry revenue uncertainty and an assumption of investment irreversibility. Results of Model 2 and 2a, which encompass opportunity cost uncertainty and costly reversion of the project, will be discussed in section 5.3. The chapter will end with a sensitivity analysis of the relevant parameters and a discussion of potential policies that could enhance the incentives to afforest private marginal land.

5.1 Budgeting (NPV) Analysis

In figure 5.1, the expected revenues to an afforestation project are presented for various carbon accounting schemes (OCs, TCs, and permanent credits¹⁶). To generate these revenues, a carbon price of \$55/tC and a stumpage value of \$12/m³ were assumed with a

¹⁶ Permanent credit scenarios refer to the allocation of units similar to ERUs but contrary to OCs no liability is assigned in case of a reversal of the sequestration process. Such a scenario is likely unacceptable due to its lack of environmental integrity but is presented here to illustrate the impact of non-permanence on the profitability of afforestation.

discount rate of 4%. In addition, the revenues needed to trigger an investment in such a project, calculated from a NPV approach, are provided as a function of the opportunity cost, i.e. agricultural revenues.

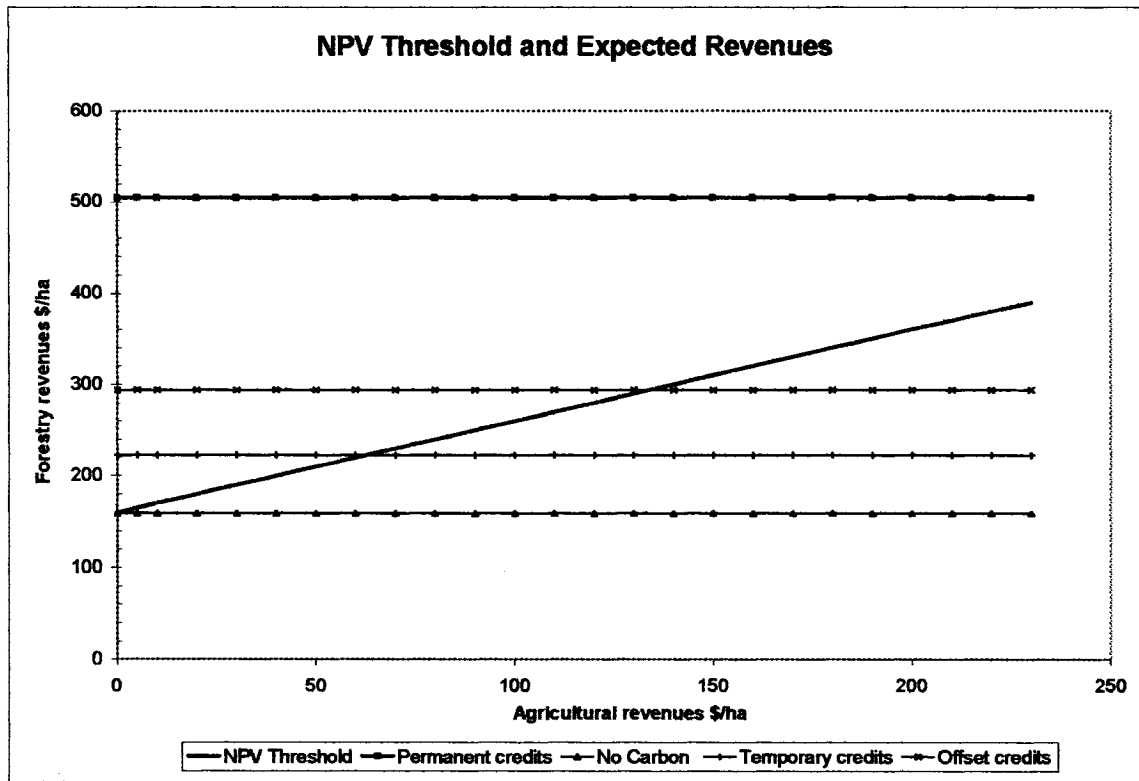


Figure 5.1: NPV investment threshold and expected revenues from various carbon accounting scheme.

It can be observed that in the absence of a carbon market, the expected revenues of the project are too low to trigger any investment in afforestation. Only when agricultural revenues fall to zero would the owner be indifferent between afforestation and agriculture. However, when carbon is valued positively, afforesting becomes a profitable option at least for land with low opportunity cost. When TCs are used to market the carbon storage services, land with an opportunity cost slightly higher than \$60/ha should

be converted, while OCs provide investment incentives to land owners with an opportunity cost around \$130/ha and granting permanent credits to such a project would convert land yielding more than \$250/ha in agricultural revenues. In light of these results, the introduction of a carbon market would seem to create incentives leading to a degree of afforestation. In accordance with expectations, accounting for non-permanence either by selling OCs or TCs instead of permanent credits reduces these incentives significantly.

In this particular case study the OCs seem to generate greater revenues than TCs. This is due to carbon contained in soil, litter and root pools which are not emptied upon harvest and hence can be considered as being permanently sequestered for the time horizon studied (24 years). Over this time horizon selling these carbon stocks for the full price through OCs is more profitable than renting them since the liability attached to OCs is not expected to come into effect. However, the liability related to those pools becomes an additional barrier to exit until the end of the liability period. Such a barrier has no impact on a static analysis such as the NPV but would be important when considering the possibility of reversion in a dynamic analysis of an investment decision.

5.2 Results from Model 1 and 1a: Real Option Analysis

As expected, the real option model leads to higher investment thresholds due to the presence of a valuable option to wait. Depending on the carbon accounting scheme and the opportunity cost chosen, the optimal investment trigger found with the real option model ranges from 1.8 to 4.3 times the NPV threshold (see figure 5.2).

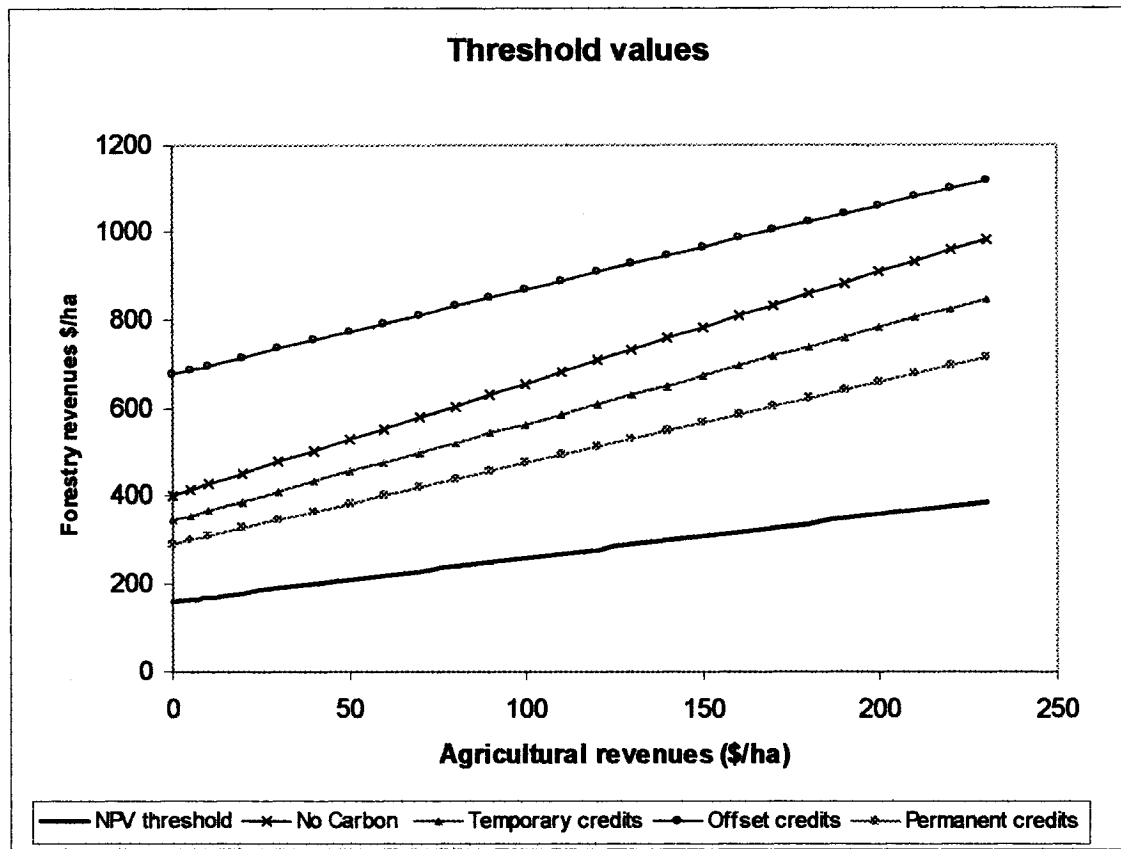


Figure 5.2: Real option investment threshold given uncertain forestry revenues and irreversible afforestation.

The base case in which there is no carbon market leads to a *real option factor*¹⁷ slightly above 2.5. In other words, to trigger investment, every dollar on the cost side must be offset by more than \$2.50 of revenues in order to compensate for the option's value of waiting to implement the project at a later date. Figure 5.3 shows the value of an option on a future afforestation project for the base case scenario given yearly agricultural revenues of \$100/ha. The option on a one hectare afforestation project is worth above

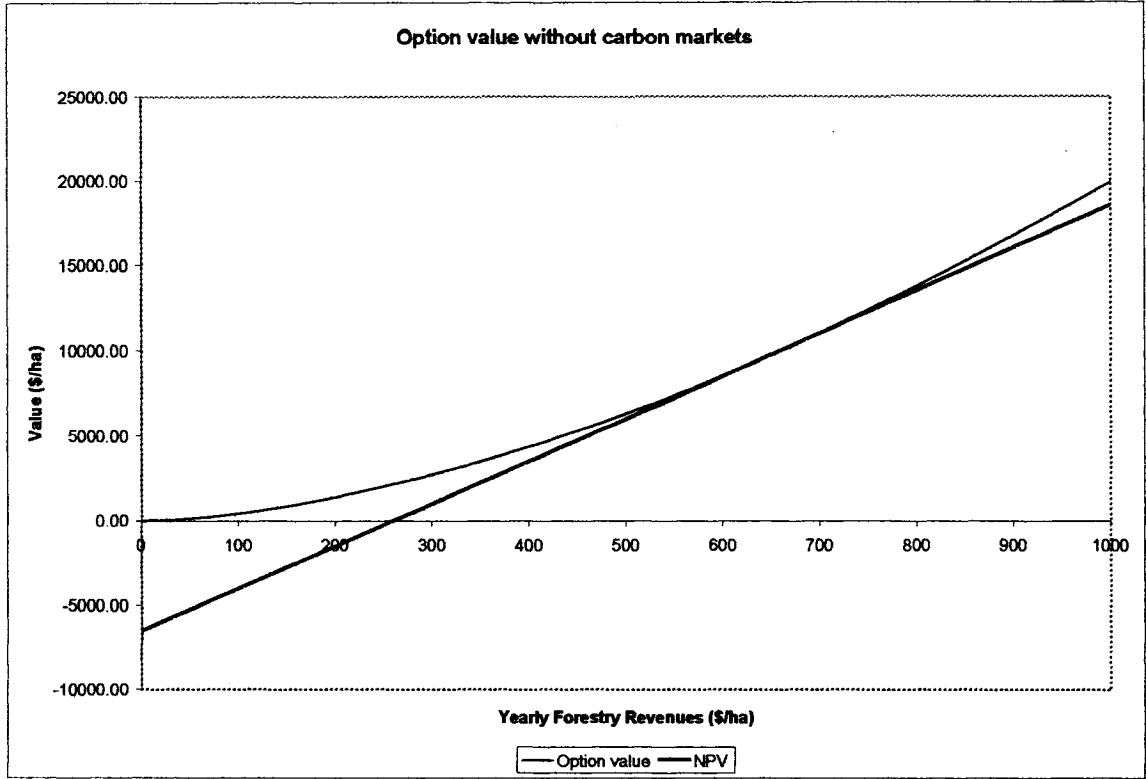


Figure 5.3: Real option value without carbon markets. $R_a = \$100/\text{ha}$, $\sigma_{\text{carbon}} = 0.25$, $\sigma_{\text{timber}} = 0.27$, $\mu_{\text{carbon}} = \mu_{\text{timber}} = 0$ and $r = 0.04$.

\$9500 when optimally exercised as yearly forestry revenue reaches \$654/ha. Additionally, the gap between the NPV threshold and the real option optimal investment trigger increases with the opportunity cost which further reduces the potential for converting land generating large agricultural revenues.

A direct implication of the presence of an option to wait before investing in afforestation is to create some friction in land use conversion. Such friction was reported in other studies such as Kurkalova et al. (2003) and Schatzki (2003). In the current model, the

¹⁷ The real option factor is represented by $\frac{\beta}{\beta-1}$ from equation 3.3, $\bar{R}_F = (r - \mu_f) \frac{\beta}{\beta-1} \left(\frac{K}{r} + \frac{R_a}{r} \right)$.

friction finds its source in the presence of sunk costs combined with uncertain revenues. Such friction in land use decisions leads to hysteresis which works to retain land in agriculture that could be more profitably used in forestry. On the other hand, once afforested the incentives needed to bring land back into agricultural production will be much greater due to the same market friction.

Introducing a carbon market

The advent of a carbon market has the effect of reducing the risk related to forestry revenues since it provides one with more diversified sources of revenues. Due to the lower level of uncertainty, downside risk decreases and the option to wait loses value. For this reason a carbon market tends to decrease the real option factor and the level of revenues needed to trigger afforestation. Permanent credits, as they generate greater carbon revenues, represent a better source of diversification and consequently reduce the volatility of forestry revenues to a greater extent than TCs. Figure 5.4 shows the option values for TC and permanent credit scenarios. At the baseline parameter value, the investment option should be exercised as forestry revenues reach \$467/ha in the case of permanent credits and \$567/ha for the temporary credits scenario.

The OC scheme also reduces the real option factor, but it increases the overall threshold due to the liability cost that it creates. Since a large part of the carbon sequestered is released upon harvest, the liability scheme increases the downside risk. As can be seen in figure 5.4, the attribution of offset credits leads to a threshold of \$868/ha in forestry

Where β is a function of revenue volatility (σ_a , σ_D), expected growth rates (μ_a , μ_D), and the discount rate (r).

revenues. The shift in the NPV curve for the OC schemes is due to the carbon liability which also tends to reduce the value of the investment option at low levels of revenues.

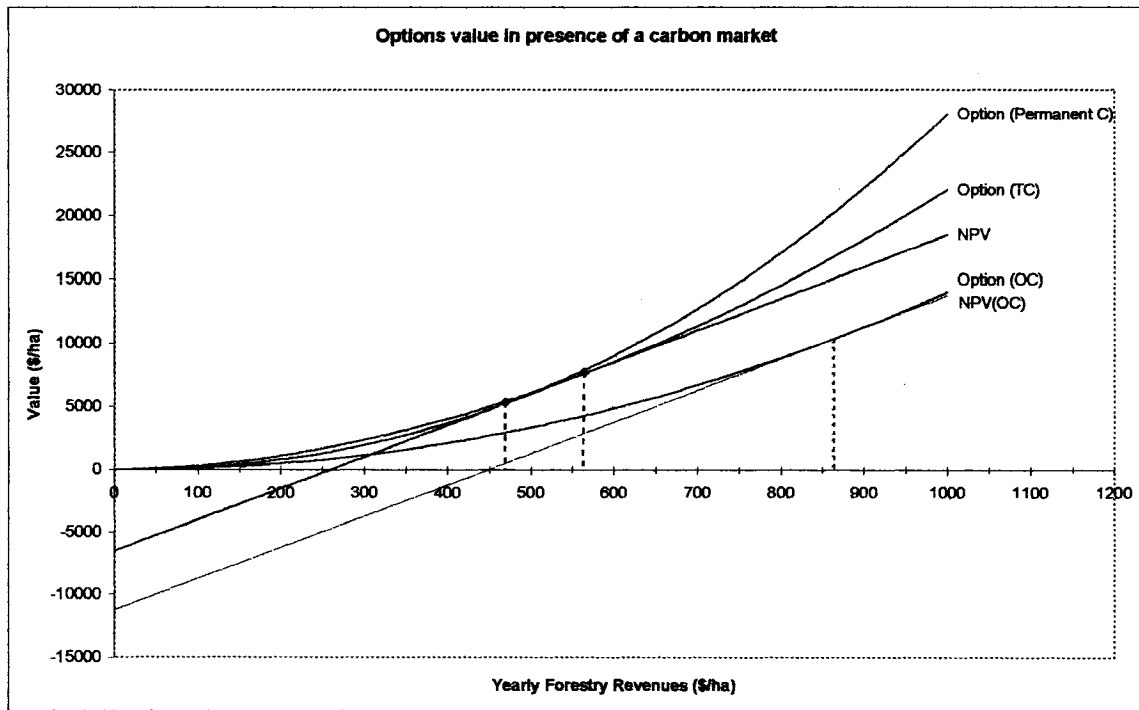


Figure 5.4: Real option value in presence of carbon markets. $R_u = \$100/\text{ha}$, $\sigma_{\text{carbon}} = 0.25$, $\sigma_{\text{timber}} = 0.27$, $\mu_{\text{carbon}} = \mu_{\text{timber}} = 0$ and $r = 0.04$.

An interesting feature of the OC scheme is that an increase in carbon prices boosts revenues but also increases the liability cost and the downside risk. For this reason the real option models indicate that OC accounting is inappropriate for the present case study. Such a result outlines the benefits of a flexible policy which allows one to choose between various carbon marketing schemes for different projects. But this also represents an important departure from the results obtained by the budgeting approach which ranked OCs as the most profitable alternative.

In summary, the carbon market not only provides an incentive by increasing revenues but also provides a source of diversification which is captured in the real option model through volatility parameters. However, in order to attract land to an afforestation program, revenues must be much higher than previously found with the budgeting approach. Although permanent credits at \$55/tC would still provide an incentive to convert land with \$120/ha in opportunity cost, if TCs are chosen to address non-permanence, the carbon price would need to attain \$143/tC in order to compensate for the option to wait on land with zero opportunity cost (see figure 5.5).

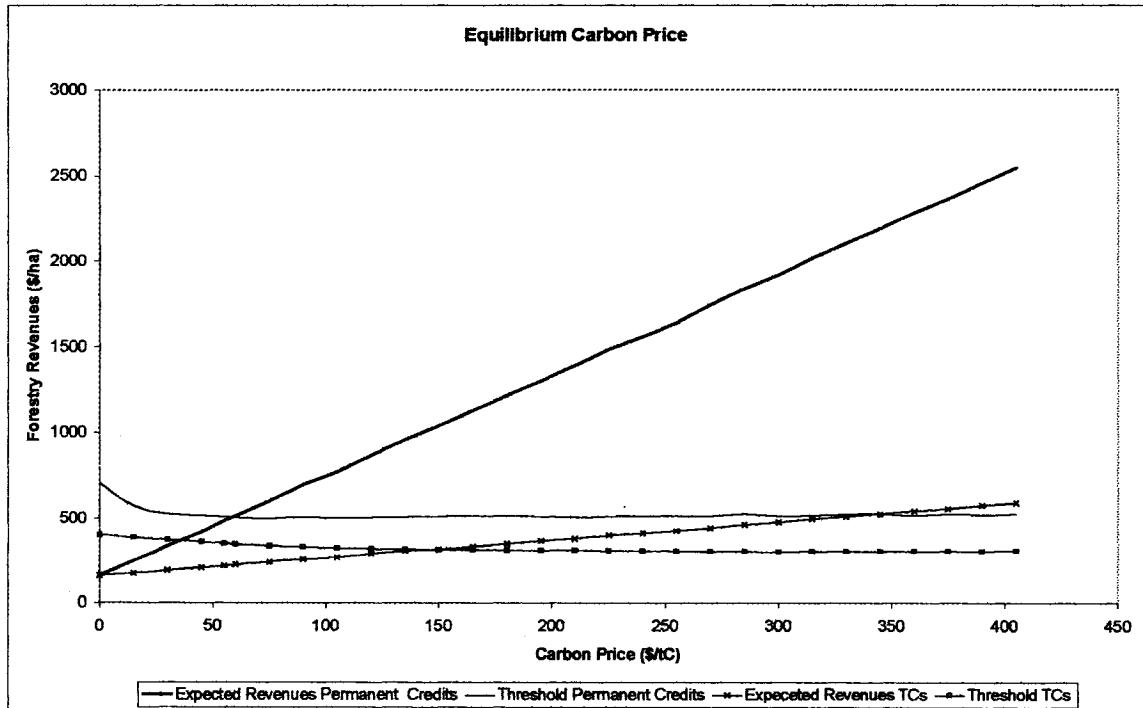


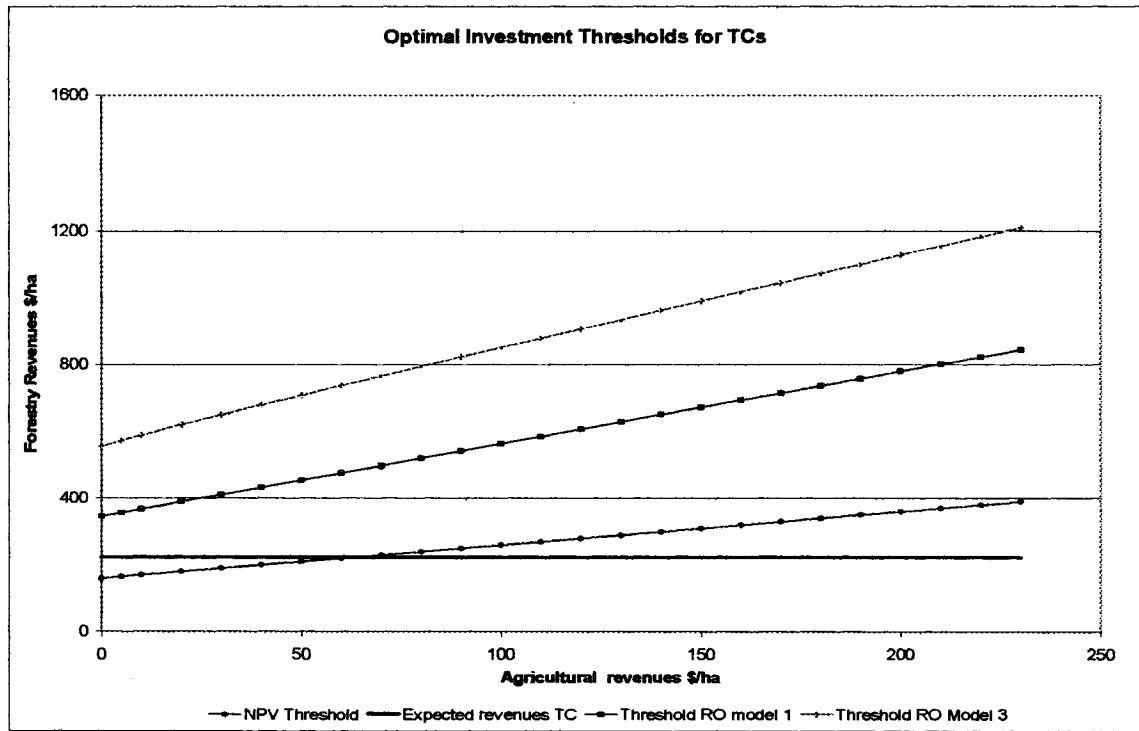
Figure 5.5: Forestry revenues and investment threshold as a function of carbon price
 $R_u = \$100/\text{ha}$, $\sigma_{\text{carbon}} = 0.25$, $\sigma_{\text{timber}} = 0.27$, $\mu_{\text{carbon}} = \mu_{\text{timber}} = 0$ and $r = 0.04$.

5.3 Results from Model 2 and 2a: Including opportunity cost uncertainty and reversibility

Results presented in section 5.2 stem from a simple model that assumes uncertainty lies only in potential revenues to forestry and investment is irreversible. However, the volatility of agricultural revenues, which represent an opportunity cost in the actual case, is well recognized. Unless they enter long term contracts, farmers are uncertain of the market price and yield for tame hay or forages. Since a change in agricultural revenues will impact the profitability of afforestation, this risk should be included in an optimal decision making process. As well, the afforestation process can certainly be reversed, although at a substantial cost¹⁸. Allowing for future reversion of the decision provides a manager with greater flexibility which should reduce the potential loss if afforestation turns out to be less profitable than agricultural production. The previous model can be used to depict the situation at the no rent margin as agricultural revenues are nil, their volatility and the possibility of reversion become insignificant. However, model 2 should provide more realistic decision rules for productive agricultural land conversion.

Figure 5.6 shows optimal investment triggers for the TC scenario when accounting for opportunity cost uncertainty and reversibility. Results from the NPV analysis and the previous real option model are also reported for sake of comparison. The large uncertainty level of agricultural revenues ($\sigma_a=0.301$) leads to a higher threshold for model 2 than what was previously found. Allowing for reversibility of investment tends to reduce the real option effect but the high cost of conversion to agriculture maintains a significant barrier to exit.

In the TC scenario, the real option factor is found to be approximately 3.5, leading to an even larger gap between expected revenues and the investment threshold at a carbon price of \$55/tC. In order to provide an afforestation incentive for land at the no-rent margin, the carbon price would have to be \$334/tC, which is unlikely to be sustainable due to the negative impact it could have on the economy. Likewise, incentives provided by permanent credits at a carbon price of \$55/tC would be just enough to afforest land generating no agricultural revenues.



**Figure 5.6: Real option investment thresholds for temporary credits scenario. $P_{\text{carbon},0}=\$12/\text{m}^3$
 $P_{\text{timber},0}=\$12/\text{m}^3$, $R_a=\$100/\text{ha}$, $\sigma_{\text{carbon}}=0.25$, $\sigma_{\text{timber}}=0.27$, $\mu_{\text{carbon}}=\mu_{\text{timber}}=0$.**

¹⁸ Cost estimates from Quebec agricultural appraisers range from \$3000/ha to \$4000/ha

The pessimistic results presented above are dependent on the assumption of non-stationary diffusion processes for commodity prices. If the true processes were stationary the investment threshold would be biased upward and the carbon price needed to trigger investment would be overestimated. Since, non-stationarity of the agricultural revenue diffusion process was put in doubt by tests performed in section 3, and since theory would suggest a stationary process for most commodities, estimates of investment barriers more robust to the non-stationarity assumption would be indicated.

To fill this gap, some key results are obtained by looking at probability of investment in afforestation projects over a given period. Figure 5.7 shows the cumulative investment probabilities obtained by Monte Carlo simulation (15000 iterations) using the real option threshold as the investment decision tool. The simulation is meant to represent a heterogeneous farm population in terms of agricultural revenue and timber price. The population variance in agricultural revenues is justified by the variation of land quality across farms. The stumpage value is expected to vary within a farm population due to changes in the distance from the mill and the impact on transportation costs. Hence, the initial timber price is assumed to be distributed normally around $\$12/\text{m}^3$ with truncations at $\$8/\text{m}^3$ and $\$16/\text{m}^3$ while agricultural revenues at time zero are distributed normally with mean $\$50/\text{ha}$ and are truncated at $\$0/\text{ha}$ and $\$100/\text{ha}$. Results from Metcalf and Hassett (1995) indicate that when using such simulation a non-stationary process leads to slightly higher probabilities than a stationary process as the variance effect tends to outweigh the realized price effect when the volatility is greater than 0.25.

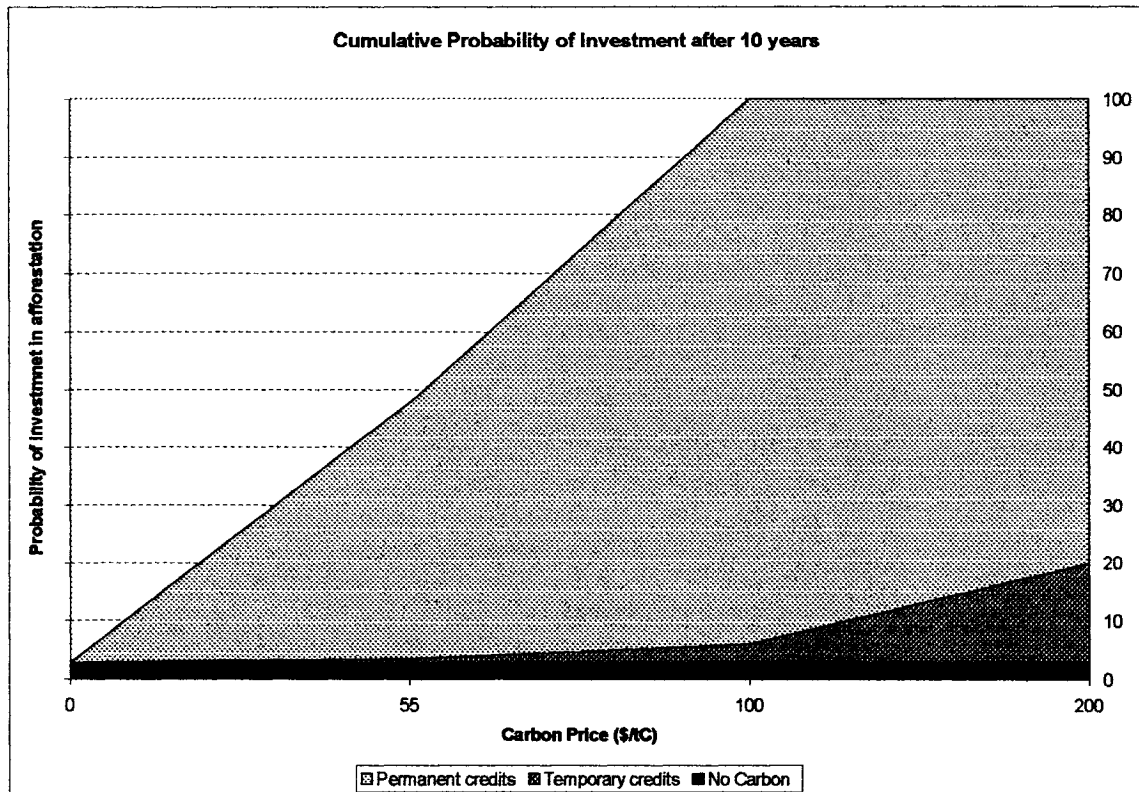


Figure 5.7: Cumulative afforestation investment probabilities over 10 years
 $\sigma_{\text{carbon}}=0.25$, $\sigma_{\text{timber}}=0.27$, $\mu_{\text{carbon}}=\mu_{\text{timber}}=0$, $r=0.04$.

Given the baseline carbon price of \$55/tC, permanent credits would lead to 48% afforestation over the 10 years period, but the probability of afforestation falls to 3.5 % when TCs are used. These numbers show the strong negative impact of non-permanence on adoption incentives. But most importantly, these results imply that even if the true diffusion processes of forestry and agricultural revenues were to follow a stationary process, the model predicts insufficient incentives to convert a sizeable share of western Canada's marginal agricultural land if non-permanence is addressed with TCs.

Increasing the initial carbon price leads to a greater probability of afforestation. A carbon price of \$100/tC would be enough under the permanent credits assumption to trigger

immediate afforestation of agricultural land generating less than \$100/ha in agricultural revenues. Yet, results presented in figure 5.7 indicate that under the TC scenario a price of \$100/tC would only generate a 6.04% probability of adoption. Even at a price of \$200/tC the cumulative probability of afforestation just reaches the 20% level.

Therefore, the conclusion that a significant barrier to afforestation of marginal agricultural land exists seems unaffected by changes in the price diffusion processes assumptions. When adding the negative impact of non-permanence, the carbon price needed to induce afforestation on a wide scale reaches the \$200/tC level or more. Non-permanence seems to be the most important factor affecting the profitability of afforestation projects. Yet the real option effect, brought about by the uncertainty of revenues and cost as well as the barriers to entry and exit created by the high cost of land conversion, reduces the probability of investment from 80% to less than 4% for the TC scenario. Hence, combined together the non-permanence and the real option effect significantly reduce the afforestation potential of marginal agricultural land. In light of these results, the implementation of this BMP in western Canada does not appear to be a low cost alternative for mitigating climate change and, thus, the number of emissions credits provided by afforestation is likely to be small.

5.4 Sensitivity analysis

Although it has been found that key implications are robust to the diffusion process assumption, results also depend on the parameters determining expectations about forestry and agricultural net revenues, their volatility, and the discount rate. All of these

may be subject to estimation error, or may be perceived differently by one individual or another. Consequently, a sensitivity index is used to explore the change in investment incentives in response to changes in parameters.

Sensitivity index:
$$\eta_r = \frac{\ln(R_2^F) - \ln(R_1^F)}{\ln(r_2) - \ln(r_1)}$$

The sensitivity indexes are given in table 5.1 and have been computed to reflect potential changes from baseline parameter values that were obtained from estimation procedures presented in chapter 3. Two indexes are presented, one with respect to the real option optimal investment threshold (R^f) and a second one with respect to the cumulative probability of investment within a decade.

First, a one percent decrease in the discount rate would raise the threshold by 0.359 percent but would reduce the probability of afforestation by 1.513 percent. This is due to the greater importance given to future revenues and uncertainties related to them. Since the option value is positively linked with variance, the threshold increases in response to a lower discount rate. On the other hand, expected revenues to afforestation are discounted less heavily. However, the effect on the option value outweighs the impact on revenues, and the end result is a smaller probability of investment due to a lower discount rate.

It should be noted that the discount rate used in this model is meant to represent the opportunity cost of capital. Hence it is subject to change as the general interest rates within the economy fluctuate. At present, inflation seems under control in Canada, and the discount rate used is not expected to vary significantly within the short or medium

term. Consequently, the relative sensitivity of the model to the choice of discount rate should not undermine the results indicating the presence of a large barrier to afforestation. Even at a rate of 8%, the real option threshold for the TC scenario is more than 2.8 times the NPV threshold and the probability of afforestation within ten years only increases to 5.7%.

Table 5.1: Sensitivity Indexes for the temporary credits scenario¹⁹

Parameters	Sensitivity index (η)	Sensitivity index (η)
	Threshold (R^f)	Cumulative Prob.
r (0.04 to 0.03)	-0.359	1.513
C^a (3000 to 2000)	0.013	n/a
μ_f (0.01 to 0.02)	-0.073	1.123
σ_f (0.22 to 0.10)	0.257	3.079
μ_a (0.01 to 0.02)	-0.018	-0.415
σ_a (0.301 to 0.20)	0.495	-1.585
C^f (1500 to 750)	0.608	-2.467

Note: The range over which the sensitivity analysis was performed is given in parentheses

Changes in the cost of conversion from forestry to agriculture (C^a) have only a limited effect as the sensitivity index (0.013) indicates. This occurs because the high conversion cost represents a sizeable barrier to exit relative to the potential benefits of the forestry activity. Hence, unless the conversion cost to agriculture is overestimated by a large amount, the impact of estimation error on the investment decision will be modest.

¹⁹ Sensitivity indexes for the permanent credits scenario are presented in appendix 3

Similarly, the real option threshold seems to be only slightly influenced by the expected growth rate of net agricultural revenues (μ_a). And although changing the expected growth rate of forestry revenues (μ_f) has a larger effect than for agricultural revenues, it too has only a limited impact on the investment incentives. Hence estimation error would have only a modest impact on the results. Likewise, if expectations of farmers about long term market trends for forage, timber and carbon, were to differ significantly, the impact would be relatively small. This can be explained by the high level of uncertainty (σ) related to those expectations which encourage landowners to wait for a higher level of profitability before committing their resources to afforestation.

The greatest responsiveness stems from changes in the uncertainty factors (σ_a , σ_f), and the sunk cost to afforestation (C^f). In particular the volatility of agricultural revenues, which is the primary source of uncertainty in the model, has the most important impact on investment threshold. On average over the range studied, i.e. 0.2 to 0.301, a one percent change in σ_a generates a 0.495 percent change in the investment threshold while a similar decrease in σ_f would lead to a decrease of 0.257 percent in the investment threshold. Both are positively correlated to the investment threshold as would be expected in a real option model.

However, the probability of afforestation is affected differently by both parameters. Raising forestry revenue volatility would increase the probability of afforestation investment while an increase in agricultural revenue volatility would decrease the same probability. This is explained by the presence of a constant term on the cost side (C^f),

hence even if agricultural revenues have more of a chance of decreasing, a minimum cost still exists. At the same time chances that agricultural revenues reach high levels have increased thus yielding a lower investment probability.

Finally, a decline in afforestation sunk cost (C^f) would significantly lessen the barrier to investment and accordingly would also increase the probability of investment. The periodicity of this cost, which is incurred after every rotation, provides for a greater effect on afforestation incentives than the conversion cost to agriculture which would be incurred only once.

5.5 Potential Policies under TC Scenario

Considering the previous results, afforestation does not appear as a low cost mitigation strategy. Nevertheless, some public policies and/or institutional designs could be developed to provide an incentive to convert marginal agricultural land to hybrid poplar plantations. Although the subsidization of afforestation for carbon sequestration purposes could be hard to defend assuming the supply of carbon credits from other sources at lower cost, some secondary benefits could justify the case. For example, the PFRA (Prairie Farm Rehabilitation Administration) has been providing planting stocks and technical advice to promote the establishment of shelterbelts to reduce erosion and water run-off. In addition, afforestation could lessen pressure on natural forest stands. A governmental subsidy for carbon sequestration also has the advantage of being a “green box” subsidy, which could make a contribution in diversifying and stabilizing farmers’ income.

Risk management:

In order to strengthen afforestation incentives, the risk related to the decision could be dampened by public policy instruments. The federal government, being itself a major buyer of GHG reduction credits, could design and offer long term contracts for carbon credits that could reduce the price risk related to carbon sinks. As well, offering risk management tools such as insurance, options or futures markets could help reduce revenue volatility. In a similar fashion, timber price risk could be mitigated by long term contracts, price insurance, or futures markets.

Removing the carbon market price risk would reduce the diversification effect and thus would likely negatively affect the investment in afforestation. However, removing the risk related to both timber and carbon prices would lead to a substantial reduction of the real option investment threshold from 3.27 to 2.68 times the NPV trigger for the TC scenario. As can be seen in figure 5.8, reducing the volatility of forestry revenues has a decreasing effect on the real option threshold. However, the minimum carbon price required to induce afforestation with TCs at the no rent margin is still quite high, at \$262/tC. Keeping the carbon price at \$55/tC, the probability of investment within ten years would be increased slightly from 3.5% to 8.1%. Therefore, on its own, this strategy is not likely to trigger massive land conversion. Even when volatility is totally eliminated and the carbon price is set at \$110/tC, the cumulative probability of investment within 10 years is only of 14.4%. Despite the positive impact on investment due to the reduction in forestry revenue risk, there is still a high investment barrier due to sunk cost and the uncertainty related to agricultural revenues.

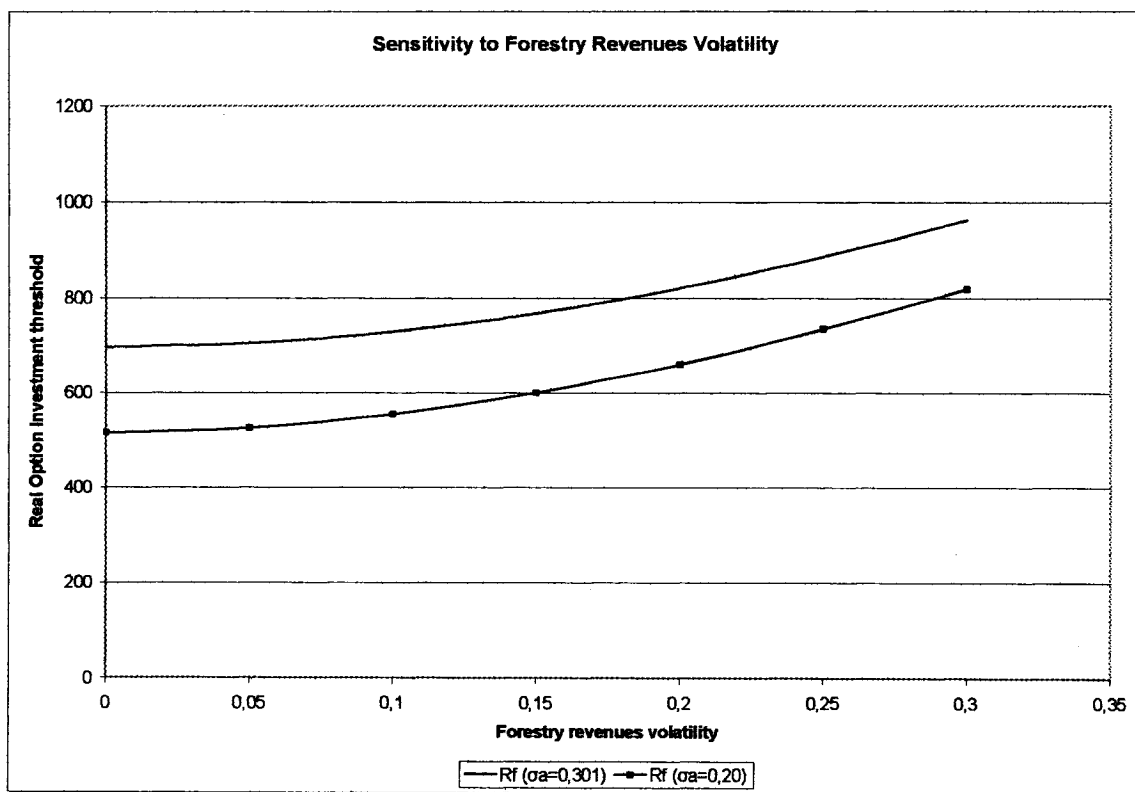


Figure 5.8: Sensitivity of the real option optimal investment threshold as a function of forestry revenues volatility.

Lowering the barrier to entry:

Another means to create clearer incentives for land conversion is to decrease the barrier to entry. For example, planting stocks can be granted through programs like the PFRA or afforestation could be directly subsidized. The impact of reducing the cost of afforestation for the first rotation is not negligible as was found by the sensitivity index in table 5.1. If the government were to cover the establishment cost for the first rotation only, the carbon price would have to rise to \$156/tC to afforest land at the no rent margin. If the authorities covered half of the establishment cost (i.e. $C^f = \$750/\text{ha}$) for all rotations

and TCs were employed, a carbon price of \$20/tC would provide enough incentive to afforest land at the no rent margin. However, the carbon price would need to rise to \$156/tC to convert land with a rental cost of \$50/ha. Similarly, reducing the establishment cost to \$750/ha leads to a 23.3% chance of afforestation within 10 years given a carbon price of \$110/tC. Therefore, this strategy is more effective than reducing forestry revenue volatility, but it may also be more costly. The range of hybrid poplar establishment costs found in the literature is quite large, from \$1200/ha to \$4000/ha²⁰ and the estimate used in this study tends toward the lower end of the range. If the costs were \$3000 or \$4000, the real option investment trigger would be much higher and to achieve the same level of conversion the cost of such a program would be seriously inflated.

Combining both policies:

A combination of policies designed to reduce risk and the barrier to entry may lead to more promising results as both are complementary. The carbon price needed to induce afforestation is presented in Figure 5.9 as a function of opportunity cost. In terms of probability of investment, a carbon price of \$55/tC leads to a probability of converting marginal agricultural land within the next decade of 22.42% on land with \$100/ha in rental cost. Increasing the carbon price to \$110/tC would raise the same probability to 38.95%. This last result is more encouraging but relies on a relatively high carbon price. As a result the creation of carbon sinks through afforestation, although potentially profitable on land at the no rent margin, may not be a low cost alternative to other mitigation plans.

²⁰ See table 4.1

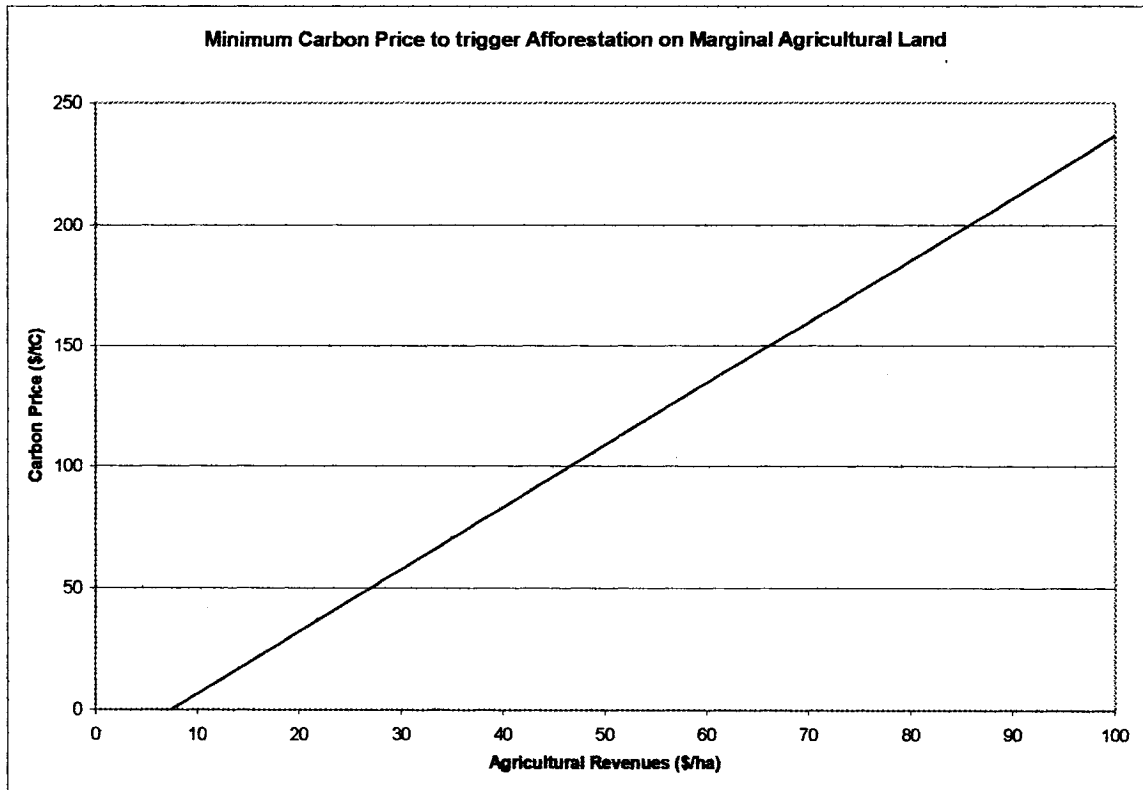


Figure 5.9: Minimum carbon price to trigger afforestation on marginal agricultural land.
 $\sigma_{\text{carbon}}=0.25$, $\sigma_{\text{timber}}=0$, $\mu_{\text{carbon}}=\mu_{\text{timber}}=0$, $r=0.04$, $C^f=\$750/\text{ha}$, $P_t=\$12/\text{m}^3$.

Chapter 6: Summary and Conclusion

6.1 Summary

The central objective of this study was to provide information to enlighten the institutional design of the offset system that will oversee the domestic GHG mitigation projects. In particular, this research investigates factors affecting a farmer's adoption of best management practices that are designed to create carbon sinks and mitigate climate change. The case of afforestation on marginal agricultural land was targeted. Previous studies have identified friction in land use change and a few potential causes were outlined, including risk and irreversibility. Building on this information, real option models were designed to assess the impact of a carbon market on the friction created by the presence of an option to wait before investing. The volatility of carbon and timber revenues were included in the model as well as the uncertainty related to agricultural revenues, which represent an opportunity cost. The models also accounted for sunk cost of forest establishment and the most complete model also included the cost of reversing the afforestation process.

In addition, the impact of non-permanence on the profitability of afforestation was analyzed to provide a more complete picture of afforestation incentives created by a carbon market. Two scenarios were developed allowing the marketing of carbon sink services either through temporary credits or offset credits with full reversal liability to the seller. For the sake of comparison a scenario that ignored the issue of non-permanence was also included in the study.

6.2 Synopsis of major findings

The creation of a carbon market would provide landowners with an opportunity to mitigate climate change and be compensated for their efforts. However, changing land use is a decision that has long term consequences and the initial investment is usually sunk. Large barriers to entry may exist for some land uses and sometimes large barriers to exit may exist by their adoption. Hence, before committing any resources in such a venture, risks and profitability must be analyzed carefully.

First, the profitability of agricultural land afforestation is affected by the ephemeral nature of the sequestration process. The imposition of a liability in case of reversal or the heavy discounting related to temporary credits reduces the afforestation incentives. The budgeting approach identified the OCs as being the most profitable option to address non-permanence since a part of the sink can be regarded as permanently sequestered over the relevant time horizon (24 years). As a result, liabilities tied to these carbon stocks are not considered as a cost. However, when including the uncertainty of revenues and the barrier to entry and exit, the OC scheme becomes less attractive than temporary credits. The option to wait is more valuable under OCs since the downside risk is larger due to the liability costs associated with the OCs. The real option model indicates that the flexibility of TCs is preferred to OCs which represents an important departure from the budgeting analysis.

On its own, accounting for non-permanence reduces the private land base that could be afforested. Under the budgeting approach, land with at most an opportunity cost of

\$134/ha could be converted to forest if non permanence is addressed through an OC liability scheme. However, permanent credits provide incentives to convert land generating as much as \$345/ha in agricultural revenues.

This study also shows that the investment decision in afforestation is far more complex than a simple budgeting exercise. The presence of large barriers to entry and exit and the uncertain revenues linked to this activity must be included in an optimal decision rule. Results of this study indicate the presence of a large barrier to investment which stems from the presence of an option to wait before investing in afforestation. The existence of this option creates friction in land use decisions and requires afforestation revenues to be much higher in order to convert marginal agricultural land to forest.

The introduction of a carbon market increases the expected revenues to afforestation and also represents a diversification opportunity which reduces the investment barrier created by the option to wait. For example, the minimum forestry revenues required to trigger afforestation goes from \$606/ha to \$555/ha when carbon sequestration services can be marketed through TCs.

Although reduced by the presence of a carbon market, the real option effect is still considerable. Under the TC scenario, the classical budgeting approach suggested that a carbon price of \$55/tC would be sufficient to profitably afforest land generating \$63/ha in rental cost. But when the option to wait is taken into account, \$55/tC would not be enough to afforest any land. The volatility of carbon and timber prices as well as

agricultural revenue volatility contributes to inflate the value of the option to wait. However, the barrier to entry created by large sunk costs and the irreversibility might be of even greater importance.

Once the non-permanence and real option effects are combined together, the potential of afforestation of marginal agricultural land in western Canada is greatly diminished. When accounting for the option to wait before afforesting and using TCs to market the carbon storage services, a carbon price above \$600/tC is required to afforest land yielding \$100/ha. As well, land at the no rent margin would require a carbon price of \$143/tC to be converted to forest.

6.3 Policy Implications

Non-Permanence:

Addressing the issue of non-permanence is crucial to preserve the environmental integrity of the Canadian GHG mitigation plan. In addition, the rules should be set in accordance with international agreements so as to obtain global recognition of the mitigation efforts undertaken. For the moment, those constraints lead to a non-permanence policy that heavily discounts carbon revenues. However, future negotiations should address alternatives such as the inclusion of wood product sinks, which are not accepted by the KP. In many cases wood products are used for long term purposes like building material that could represent an effective means of sequestering carbon over long periods. Van Kooten et al. 2004 present the inclusion of wood product sinks as being a key factor in

determining the competitiveness of the forestry option. This study also supports this view by reporting a large negative impact of non-permanence on incentives to afforest.

Real Option Effect:

The option to wait before converting agricultural land to forest has a significant impact on the optimal investment rule. In order to encourage BMPs adoption, policymakers should try to minimize the option value that is created by the sunk cost involved in the project as well as the uncertainty of revenues. Although agricultural revenues contribute to the uncertainty of the project, attempting to stabilize them in favor of creating carbon sinks through afforestation may not be a well targeted policy. However, the uncertainty of forestry revenues could be dampened by offering long term contracts, price floors, or other risk management tools such as futures or options for carbon and timber products. Yet, according to the results, the most effective means of reducing the barrier to investment created by real options is to combine a decline in forestry revenue volatility with a reduction in the establishment cost. Such a strategy could lead to a 37.7% probability of afforestation within 10 years given TCs and a carbon price of \$55/tC which is relatively low. The reduction in sunk cost related to the establishment of the forest stand could take the form of free planting stocks or a direct subsidy. Subsidizing the early investment cost of afforestation may provide one with long term benefits as the hysteresis created by the real options will tend to prevent future deforestation on those land tracks. Besides, the ancillary benefits of afforesting some agricultural land, such as a reduction of soil erosion, should be taken into account and may justify a certain level of subsidy as is the case with the PFRA program.

However, marginal agricultural land afforestation should not be seen as a low cost alternative to other GHG mitigation strategies. In addition to market uncertainty and barriers to entry and exit, other obstacles remain. These include such things as transaction costs and carbon credit aggregation issues. Hence, if the carbon price is expected to stay below the \$100/tC level, the expectation for carbon credits from afforestation projects should be modest.

6.4 Limitations and Further Research

In addition to the classical budgeting approach this study accounted for risk and irreversibility in an attempt to estimate the barrier to investment in carbon sink projects and analyze potential policy impacts. However, a few extensions to this research can be proposed to improve the completeness of the study.

First, similar studies could be extended to other BMPs such as no-till farming and manure management. Information stemming from those studies would be useful in assessing the overall impact of an offset system on the farming community.

Also, the modeling approach used in this study included various sources of uncertainty and risk, yet risk attitudes of landowners were not considered. Including the impact of landowners' risk attitudes may affect the results. In particular, if a policy is designed to reduce the volatility of forestry revenues, then afforestation may become more attractive to risk averse landowners. Following the same line of reasoning, the present study analyzed the potential switch of a hectare of land, but the diversification impact of forestry revenues within a complete farm business was not considered. The inclusion of

carbon and timber revenues may provide diversification benefits to a farm business which would be beneficial to risk averse farmers. The potential for afforestation on marginal agricultural land could be increased by a combination of risk aversion and the diversification effect.

6.5 Conclusion

Addressing the climate change problem is one of the most pressing issues at the global scale and Canada has committed to reducing its GHG emissions below its 1990 level. Canada has for a long time seen its large agricultural and forestry land base as an important asset in fulfilling its Kyoto commitment. However, carbon sinks pose problems due to their ephemeral nature. This study suggests that the policies proposed to address the problem of non permanence do not provide the incentive for agricultural land afforestation.

In addition, the risk inherent in the implementation of BMPs and the carbon market that is new and unproven, combined with the sunk cost related to carbon sinks creates a large barrier to investment. Although the study targeted afforestation projects the conclusion may be relevant to other BMPs that entail sunk costs and for which revenues are uncertain. Hence, risk and irreversibility related to the creation of carbon sinks may significantly reduce the GHG mitigation potential outlined by previous studies.

References:

1. Agriculture and Agri-Food Canada, PFRA Shelterbelt Center. 2005. *Consideration for Hybrid Poplar Production*. Indian Head, Saskatchewan.
www.agr.ca/pfra/shelterbelt.htm
2. Agriculture and Agri-Food Canada. PFRA Shelterbelt Center. 2001. *Growing Hybrid Poplars as a Crop*. Indian Head, Saskatchewan.
http://www.agr.gc.ca/pfra/shelterbelt/gpoplar_e.pdf
3. Alberta Agriculture, Food and Rural Development. 2003. *Agriculture Business Profiles: Private Woodlot Enterprises*. Agdex 300/830-1, September.
4. Antle, J., S. Capalbo, S. Mooney, E. Elliott, and K. Paustian. 2002. "A Comparative examination of the efficiency of sequestering carbon in US agricultural soils." *American Journal of Alternative Agriculture* 17(3):109-115.
5. British Columbia Ministry of Forestry, Revenue Branch. 2004. *Log Market Reports*. Accessed May 2, 2005.
<http://www.for.gov.bc.ca/hva/timberp/amv.htm>
6. Cairns Michael A., Sandra Brown, Eileen H. Helmer, and Greg A. Boumgardner. 1997. "Root biomass allocation in the world's upland forest." *Oecologia* 111(1):1-11.
7. Carey, Janis, and David Zilberman. 2002. "A Model of Investment under Uncertainty: Modern Irrigation Technology and Emerging Markets in Water." *American Journal of Agricultural Economics* 84 (1):171-183.
8. Chomitz, Kenneth M. 2000. *Evaluating Carbon Offsets from Forestry and Energy Projects: How Do They Compare?* Working Paper No.2357. World Bank, Development Research Group, Washington DC.
9. Christoffersen, Peter. 2003. *Implementing a \$15 Price Cap on Domestic Trading CO2 Emissions*. Natural Resource Canada, Ottawa: Ontario October 2003.

10. Colombia, Ministry of the Environment. 2000. *Expiring CERs, A proposal to addressing the permanence issue*. In United Nations Framework Convention on Climate Change. UNFCCC/SBSTA/2000/MISC.8. Submitted 13 Sept. 2000, pp.23-26. Available at www.unfccc.int.
11. Diederer, P., H. van Meijl, A. Wolters, and K. Bijak. 2003a. "Innovation adoption in agriculture: innovators, early adopters and laggards." INRA. *Cahier d'Économie et Sociologie Rurale* 67 (2):29-50.
12. Diederer, Paul, Frank Van Tongeren, and Hennie Van Der Veen. 2003b. "Returns on Investments in Energy-saving Technologies Under Energy Price Uncertainty in Dutch Greenhouse Horticulture." *Environmental and Resource Economics* 24:379-394.
13. Dixit, Avinash K., and Robert S. Pindyck. 1994. *Investment Under Uncertainty* Princeton, New Jersey: Princeton University Press.
14. Elliot, Graham, Thomas J. Rothenberg, and James H. Stock. 1996. "Efficient Tests for an Autoregressive Unit Root." *Econometrica* 64 (4):813-836.
15. Enders, Walter. 1995. *Applied Econometric Time Series*. New York: John Wiley & Sons
16. Globe and Mail. November 19, 2004. "*Canada will be champion of Kyoto, Dion vows.*" page A9.
17. Government of Canada. 2005. "Project Green: A Plan for Honouring our Kyoto Commitment." Supply and Services, Ottawa.
18. Guy, R.D. and A. Benowicz. 1998. "Can Afforestation Contribute to a Reduction in Canada's Net CO₂ Emissions?" Department of Forest Sciences, University of British Columbia.
19. IPCC (Intergovernmental Panel on Climate Change). 2001a. "Climate Change 2001: Synthesis Report." Cambridge, UK: Cambridge University Press.
20. IPCC (Intergovernmental Panel on Climate Change). 2001b. "Climate Change 2001: Impacts, Adaptation, and Vulnerability." Cambridge, UK: Cambridge University Press.

21. IPCC (Intergovernmental Panel on Climate Change). 2003. "Good Practice Guidance for Land Use, Land-Use Change and Forestry." Ed. J. Penman et al. IPCC National Greenhouse Gas Inventories Program.
22. Khanna, Madhu, Murat Isik, and Alex Winter-Nelson. 2000. "Investment in site-specific crop management under uncertainty: implication for nitrogen pollution control and environmental policy." *Agricultural Economics* 24:9-21.
23. Kiecker and Schoessow. 2000. *Hybrid Poplar Budget*. University of Wisconsin Extension, Agriculture and Natural Resource Department,
24. Kort, J, and R. Turnock. 1999. "Annual Carbon Accumulations in Agroforestry Plantations." Agriculture and AgriFood Canada, PFRA Shelterbelt Center. Indian Head, Saskatchewan.
25. Kurkalova, Lyubov, Catherine Kling and Jinhua Zhao. 2003. "Green Subsidies in Agriculture: Estimating the Adoption Costs of Conservation Tillage from Observed Behavior." Working Paper 01-WP 286, Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa.
26. Lecocq, Franck. 2004. "State and Trends of the Carbon Market 2004." Development Economics Research Group, World Bank, Washington DC.
27. Manley, James, G. Cornelis Van Kooten, Klaus Moeltner, and Dale W. Johnson. 2005. "Creating Carbon Offsets in Agriculture Through No-Till Cultivation: A Meta-Analysis of Costs and Carbon Benefits." *Climatic Change* 68(1):41-65.
28. Mansfield, Eldwin. 1961. "Technical Change and the rate of Imitation" *Econometrica* 29 (4):741-766.
29. Marra, Michele, David J. Pannell, Amir Abadi Ghadim. 2003. "The economics of risk, uncertainty, and learning in the adoption of new agricultural technologies: where are we on the learning curve?" *Agricultural Systems* 75:215-234.
30. McCarl, Bruce A., and Uwe A. Schneider. 2000. "U.S. Agriculture's Role in a Greenhouse Gas Emission Mitigation World: An Economic Perspective." *Review of Agricultural Economics* 22 (1):134-159.
31. McDonald, Robert, and Daniel R. Siegel. 1986. "The Value of Waiting to Invest." *The Quarterly Journal of Economics* 101:707-728.

32. McKenney, Daniel W., D. Yemshanov, G. Fox, E. Ramlal. 2004. "Cost estimates for carbon sequestration from fast growing poplar plantations in Canada." *Forest Policy and Economics* 6:345-358.
33. Metcalf, Gilbert E., and Kevin A. Hassett. 1995. "Investment under alternative return assumptions: Comparing random walks and mean reversion." *Journal of Economic Dynamics and Control* 19:1471-1488.
34. Mills, Terence C. 1990. *Time series techniques for economists*. Cambridge, Cambridge University Press.
35. Ng, Serena, and Pierre Perron. 2001. "Lag Length Selection and the Construction of Unit Root Tests with Good Size and Power." *Econometrica* 69 (6):1519-1554.
36. Pagano, Amy Purvis. 1993. "Ex Ante Forecasting of uncertain and irreversible dairy investments: Implication for environmental compliance." PhD Dissertation, University of Florida.
37. Parks, Peter J. 1995. "Explaining Irrational Land Use: Risk Aversion and Marginal Agricultural Land." *Journal of Environmental Economics and Manangement* 28(1):34-47.
38. Parks, Peter J. and Ian W. Hardie. 1995. "Least-Cost Forest Carbon Reserves: Cost-Effective Subsidies to Convert Marginal Agricultural Land to Forests." *Land Economics* 71(1):122-136.
39. Pautsch, Gregory R., L.A. Kurkalova, B.A. Babcock, and C.L. Kling. 2001. "The Efficiency of Sequestering Carbon in Agricultural Soils" *Contemporary Economic Policy* 19(2):123-134.
40. Pindyck, Robert S. 1991. "Irreversibility, Uncertainty, and Investment." *Journal of Economic Literature* 29:1110-1152.
41. Plantinga, Andrew J., Thomas Mauldin and Douglas J. Miller. 1999. "An Econometric Analysis of the Costs of Sequestering Carbon in Forests" *American Journal of Agricultural Economics* 81(3):812-824.
42. Price, Jeffrey T., and Michael E. Wetzstein. 1999. "Irreversible Investment Decisions in Perennial Crops with Yield and Price Uncertainty." *Journal of Agricultural and Resource Economics* 24(1):173-185.

43. Richards, Kenneth R. 1997. "Estimating Costs of Carbon Sequestration for a United States Greenhouse Gas Policy." Report prepared for Charles River Associates.
44. Richards, Kenneth R. and Carrie Stokes. 2004. "A Review of Forest Carbon Sequestration Cost Studies: A Dozen Years of Research." *Climatic Change* 63:1-48.
45. Rogers, Everett. 1962. *Diffusion of Innovations*. New York: Free Press of Glencoe
46. Saskatchewan Agriculture, Food, and Rural Revitalization, Policy Branch. 2003a. *Agricultural Statistics 2003*. Regina, Saskatchewan.
47. Saskatchewan Agriculture, Food, and Rural Revitalization. 2003b. *Dryland forage production costs 2003*. Accessed May 2, 2005.
http://www.agr.gov.sk.ca/docs/crops/forage_pasture/forage_management_production/drylandforage03.asp
48. Saskatchewan Crop Insurance. 2005. *Forage programs*. Accessed June 1st 2005,
<http://www.saskcropinsurance.com/programs/2005/Forage/irrtimhay.shtml>
49. Saskatchewan Forest Center, Agroforestry Unit. 2003. *A Guide to Hybrid Poplar Revenues and Costs*. May.
50. Schatzki, Todd. 2003. "Options, Uncertainty and Sunk Costs: an empirical analysis of land use change." *Journal of Environmental Economics and Management* 46(1):86-105.
51. Schneider, Uwe A. 2002. "The Cost of Agricultural Carbon Savings." Working Paper 02-WP 306, Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa.
52. Schneider, Uwe A., and Bruce A. McCarl. 2002. "The Potential of U.S. Agriculture and Forestry to Mitigate Greenhouse Gas Emissions: An Agricultural Sector analysis." Working Paper 02-WP 300, Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa.
53. Smith, J.E., and L.S. Heath. 2002. *A model of forest floor carbon mass for United States forest types*. Newton Square, PA: USDA Forest Service, Res. Pap.NE-722.

54. Stanton, B., Jake Eaton, Jon Johnson, Don Rice, Bill Schuette, and Brina Moser. 2002. "Hybrid Poplar in the Pacific Northwest : The Effects of Market-Driven Management." *Journal of Forestry* June 2002, p. 28-33
55. Statistics Canada. CANSIM II. Accessed on May 2, 2005.
<http://dc2.chass.utoronto.ca/cansim2/English/index.html>
56. Stavins, Robert R. 1999. "The Costs of Carbon Sequestration: A Revealed-Preference Approach." *The American Economic Review* 89(4):994-1009.
57. Stavins, Robert N., and Adam B. Jaffe. 1990. "Unintended Impacts of Public Investments on Private Decisions: The Depletion of Forested Wetlands." *The American Economic Review* 80(3):337-352.
58. Sunding, David L., and David Zilberman. 2001. "The agricultural innovation process: research and technology adoption in a changing agricultural sector." In *Handbook of Agricultural Economics*, Amsterdam: North-Holland, pp.207-261.
59. Trigeorgis, Lenos. 1996. *Real options: managerial flexibility and strategy in resource allocation*. Cambridge, Massachusetts: MIT Press.
60. United Kingdom Government. 2003. *Energy White Paper: Our energy future-creating a low carbon economy*. London, UK, DTI publications.
61. UNFCCC. 2002. "Methodological Issues: Land-Use, Land-Use Change and Forestry. Submissions from Parties." UNFCCC/SBSTA/2000/MISC.22 Submitted 6 Sept., 2002. Available at www.unfccc.int.
62. UNFCCC. 2005. "Essential Background: Feeling the Heat." Accessed June 1st 2005. Available at http://unfccc.int/essential_background/items/2877.php
63. U.S. Environmental Protection Agency. "SO₂ Allowance Price Index." Accessed March 14th 2005.
Available at <http://www.epa.gov/airmarkets/trading/so2market/alprices.html>
64. Van Kooten, G. C. 2000. "Economic Dynamics of Tree Planting for Carbon Uptake on Marginal Agricultural Lands." *Canadian Journal of Agricultural Economics* 48 (1)51-65.
65. Van Kooten, G. Cornelis, Brad Stennes, Emina Krcmar –Nozic, and Ruud van Gorkom. 1999. "Economics of fossil fuel substitution and wood product sinks

- when trees are planted to sequester carbon on agricultural lands in western Canada.” *Canadian Journal of Forestry Research* 29:1669-1678.
66. Van Kooten, G. Cornelis, Brad Stennes, Emina Krcmar –Nozic, and Ruud van Gorkom. 2000. “Economics of afforestation for Carbon Sequestration in Western Canada.” *The Forestry Chronicle* 76:165-172.
 67. Van Kooten, G. Cornelis, Sabina Lee Shaikh, and Pavel Suchanek. 2002. "Mitigating Climate Change by Planting Trees: The Transaction Costs Trap." *Land Economics* 78:559-572.
 68. Van Kooten, G. Cornelis, Alison J. Eagle, James Manley, and Tara Smolak. 2004. “How costly are carbon offsets? A meta-analysis of carbon forest sinks.” *Environmental Science & Policy* 7:239-251.
 69. Wang, Dabin, and William G. Tomek. 2004. “Commodity Prices and Unit Root Tests”, Paper presented at th NCR-134 Conference on Applied Commodity Price Analysis, Forecasting, and Market Risk Management, St-Louis, Missouri, April 19-20.
 70. Winter-Nelson, Alex, and Koffi Amegbeto. 1998. “Option Values to Conservation and Agricultural Price Policy: Application to Terrace Construction in Kenya” *American Journal of Agricultural Economics* 80:409-418.

Appendix 1

Estimation of GBM parameters

Given that R obeys: $dR = R \cdot \mu \cdot dt + R \cdot \sigma \cdot dz$ where $dz = e_i \sqrt{dt}$ and $e_i \sim N(0,1)$

And therefore $R_t = R_0 \cdot e^x$ where $dx = (\mu - 1/2 \cdot \sigma^2) \cdot dt + \sigma \cdot dz$

Then $\ln(R_t/R_0) = x$

And by Ito's lemma:

$$d(\ln R) = \frac{\partial \ln R}{\partial R} \cdot dR + \frac{\partial \ln R}{\partial t} \cdot dt + \frac{1}{2} \frac{\partial^2 \ln R}{\partial R^2} \cdot (dR)^2 + \frac{1}{2} \frac{\partial^2 \ln R}{\partial t^2} \cdot (dt)^2 + \frac{1}{2} \frac{\partial^2 \ln R}{\partial R \cdot \partial t} \cdot (dR)(dt)$$

$$d(\ln R) = \frac{1}{R} dR + 0 - \frac{1}{2} \frac{1}{R^2} (dR)^2 + (0)dt$$

$$d(\ln R) = \mu dt + \sigma dz - \frac{1}{2} \mu^2 (dt)^2 + \sigma^2 dt + 2\mu \sigma dt dz$$

$$d(\ln R) = \mu dt + \sigma dz - \frac{1}{2} \sigma^2 dt$$

$$d(\ln R) = \left(\mu - \frac{1}{2} \sigma^2\right) dt + \sigma dz$$

$$\text{Discretization yields: } \ln R_t - \ln R_0 = \left(\mu - \frac{1}{2} \sigma^2\right)(t - t_0) + \sigma \cdot e_i \cdot \sqrt{t - t_0} \quad (1)$$

Then:

$$\frac{\sum_{t=1}^N \ln\left(\frac{R_{t+x}}{R_t}\right)}{N} \Rightarrow E\left[\ln\left(\frac{R_{t+x}}{R_t}\right)\right] = \left(\mu - \frac{1}{2} \cdot \sigma^2\right) \cdot x$$

Where x is the number of years between returns

And

$$\begin{aligned} Var\left(\ln\left(\frac{R_{t+x}}{R_t}\right)\right) &= E\left[\ln\left(\frac{R_{t+x}}{R_t}\right) - E\left[\ln\left(\frac{R_{t+x}}{R_t}\right)\right]\right]^2 \\ \frac{1}{N-1} \cdot \sum_{t=1}^N \left[\ln\left(\frac{R_{t+x}}{R_t}\right) - E\left[\ln\left(\frac{R_{t+x}}{R_t}\right)\right]\right]^2 &\Rightarrow E\left[\ln\left(\frac{R_{t+x}}{R_t}\right) - E\left[\ln\left(\frac{R_{t+x}}{R_t}\right)\right]\right]^2 \end{aligned}$$

$$\hat{\sigma} = \left\{ \frac{1}{N-1} \cdot \sum_{t=1}^N \left[\ln \left(\frac{R_{t+x}}{R_t} \right) - \frac{\sum_{t=1}^N \ln \left(\frac{R_{t+x}}{R_t} \right)}{N} \right]^2 \cdot x \right\}^{1/2} \quad (2)$$

And

$$\hat{\mu} = \frac{\sum_{t=1}^N \ln \left(\frac{R_{t+x}}{R_t} \right)}{x \cdot N} + \frac{\hat{\sigma}^2}{2} \quad (3)$$

Testing the significance of the drift parameter μ :

The standard deviation of the mean ($\hat{\mu}$) is defined as:

$$Var(\hat{\mu}) = \frac{1}{N^2} \left[\sum_{i=1}^N Var(\mu_i) + \sum_i \sum_j Cov(\mu_i, \mu_j) \right]$$

Assuming that error terms are i.i.d.:

$$Var(\hat{\mu}) = \frac{1}{N^2} \left[\sum_{i=1}^N Var(\mu_i) \right] = \frac{N \cdot \sigma^2}{N^2} = \frac{\sigma^2}{N}$$

T-test:

$$H_0 : \mu \neq 0$$

$$t = \frac{\hat{\mu}}{\hat{\sigma} / N^{1/2}} \sim t_{(N-1)}$$

Results:

	$\hat{\mu}$	$\hat{\sigma}^2$	t statistic	Critical value ²¹
Net real ag. Revenues (1971-2002)	0.025	0.301	0.62	1.697
Net real timber revenues (1981/01-2004/12)	-0.05	0.261	2.929	1.645
Net real timber revenues (1984/06-2004/12)	-0.01	0.272	0.820	1.645

²¹ Critical value for a two tail test at 10% level of significance

Appendix 2

Expected revenues:

Given $P_t^C = P_0^C$ and $P_t^r = P_0^r$

Compute for $t=[0,24]$:

$$R^r = \sum_{i=1}^2 V(iT) \cdot P_{iT}^r \cdot e^{-riT}$$
$$R^C = \sum_{t=1}^T S(t) \cdot P_t^C \cdot e^{-rt} - \sum_{i=1}^2 L_{iT} \cdot e^{-riT}$$

Total expected forestry revenues: $R^r + R^C$

Simulated Revenues:

Given $P_{t+1}^C = P_t^C \cdot e^{(\mu_c - \sigma_c^2/2)\Delta t + \sigma_c \Delta t^{1/2} \varepsilon_{c,t}}$ and $P_{t+1}^r = P_t^r \cdot e^{(\mu_r - \sigma_r^2/2)\Delta t + \sigma_r \Delta t^{1/2} \varepsilon_{r,t}}$

Where $\varepsilon_{i,t}$ are i.i.d. $\sim N(0,1)$

Compute for $t=[0,24]$:

$$R^r = \sum_{i=1}^2 V(iT) \cdot P_{iT}^r \cdot e^{-riT}$$
$$R^C = \sum_{t=1}^T S(t) \cdot P_t^C \cdot e^{-rt} - \sum_{i=1}^2 L_{iT} \cdot e^{-riT}$$

Total simulated forestry revenues: $R^r + R^C$

Variance Estimate:

$$Var[R_t] = E[R_t - E[R_t]]^2 \approx \frac{\sum [R_t - E[R_t]]^2}{N}$$

Where N represents the number of simulations (N=25 000)

From the assumption of Geometric Brownian motion, we know that:

$$Var[R_t] = E[R_t]^2 (e^{\sigma^2 t} - 1)$$

Hence:

$$\hat{\sigma} = \sqrt{\ln \left(\frac{Var[R_t]}{E[R_t]^2} + 1 \right) \cdot t^{-1}}$$

Appendix 3

Sensitivity Indexes for the permanent credits scenario

Parameters	Sensitivity index (η)	Sensitivity index (η)
	Threshold (R^f)	Cumulative Prob.
r (0.04 to 0.03)	-0.244	-0.517
μ_f (0.01 to 0.02)	-0.063	0.528
σ_f (0.22 to 0.10)	0.115	0.219
μ_a (0.01 to 0.02)	0.104	-0.346
σ_a (0.301 to 0.20)	0.449	-1.138
C^f (1500 to 750)	0.066	-0.490
C^a (3000 to 2000)	0.033	n/a